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FACTORS AFFECTING THE CORPORATE DECISION-MAKING PROCESS OF AIR TRANSPORT MANUFACTURERS

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by

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FOREWORD

This report was prepared under Contract Number NASW-2970, with NASA Headquarters, Aircraft Energy Efficiency Office. Dr. John M. Klineberg was the Technical Monitor. The period of performance was from July 1 through December 15, 1976. Appendix A "Structured Data and Analyses" was prepared by Dr. J. D. Hill. Appendix B "Technical Considerations for Introducing Advanced Composites Into Civil Transport Airframes" was prepared by Dr. B. R. Noton. The Project Leader was Mr. R. G. Ollila.

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INTRODUCTION

U. S. airframe manufacturers have dominated the world market for passenger aircraft since the advent of jet-powered planes in the late 1950's. This dominance, the direct result of superior technology, was so complete that practically every airline in the non-communist world flies aircraft manufactured in the United States. A number of benefits accrued to the U.S. because of the phenomenon:

- U.S. airframe and engine manufacturers, as well as subcontractors, prospered to an extraordinary degree during the period of peak demand for their products, creating innumerable jobs throughout the U.S. economy.
- The sale of aircraft and parts overseas was a significant source of foreign exchange for the U.S. during a period when balance of payment difficulties were a major national economic problem. Similarly, U.S. airlines purchased primarily from domestic rather than foreign sources and this also was an important positive element in preserving a precarious national economic position.

U. S. dominance of world markets during the late 50's and through the decade of the 60's was the result of superior technology. Foreign manufacturers were unable to provide aircraft that could move people as cheaply as could U.S. aircraft manufacturers. Foreign aircraft, principally of British and French origin, were sold on a limited basis in this country. Many of these foreign built aircraft have since been replaced by more efficient U.S. built transports.

The conditions that prevailed through this period of U.S. dominance have radically changed. The free World has experienced simultaneous recession and inflation, and operating costs have dramatically climbed as a result of increased fuel costs. These forces have had a drastic effect on the economic health of both U.S. manufacturers and airlines. Equally significant, the technical competence of foreign manufacturers has increased to the point where it can be considered to be on par with that of U.S. producers. The overcapacity that currently exists in some airlines will preclude their purchasing new aircraft for some years to come, but eventually rising traffic and retirement of existing aircraft will create a demand for new transports. This market may not develop until late in the 1980's, but the producers that will dominate it will most likely be those that offer advanced technology at the lowest cost. In light of all projections, fuel economy, translated into costs per seat mile, will be one of the dominant factors. Accordingly, it is essential that U.S. manufacturers prepare themselves so that they might participate in the future sale of civilian transports, at least on a fair-share basis.

Having recognized that fuel economy would be a pivotal question influencing the future sale and utilization of commercial aircraft, the U.S. Senate in early 1975 asked NASA to conduct a study to establish reasonable goals and a plan for developing improved aircraft by the mid-1980's. As a result of that study, the NASA Aircraft Energy Efficiency (ACEE) Office was established.

The ACEE Office has management responsibility for technology programs intended to improve the fuel efficiency of future civil transport aircraft and to disseminate this technology in an orderly and timely fashion. The ACEE Office has developed a program which is intended to accelerate the readiness of advanced technologies for energy-efficient aircraft. The program directs the research and development activities of the NASA aeronautical research centers and their contractors on advanced technology, which offers significant advantages from a balanced consideration of performance, fuel efficiency, reliability, and cost reduction. Specifically, the program is divided into five technical thrusts, three under airframe technology and two under engine technology as follows:

Airframe Technology

- Energy Efficient Transport
- Laminar Flow Control
- Composite Primary Aircraft Structures

Propulsion System Technology

- Engine Component Improvement
- Energy Efficient Engine.

To maximize the benefits from this program, the ACEE program managers must select the most promising technologies and support them to the point at which manufacturers will continue development and incorporate them into future aircraft and engines.

The decision to launch a program to develop a new aircraft or engine represents a major financial hazard to even the strongest airframe and engine manufacturers. In the air transport industry, manufacturers have risked one, two, and even four times their net worth to launch a major civil transport aircraft. In contrast, established companies in other U.S. industries rarely enter into a situation where the failure of a new product could ruin the organization. They are more diversified, have a strong capital and financial base, and a large potential pool of customers. Failure of a new venture rarely can have the same effect as it would in the airframe industry.

When large companies take such extremely high financial risks, it is desirable to minimize the technical risks involved to provide the greatest possible chance for financial success. Therefore, it is important that the launch of a new transport program be undertaken only when it can be demonstrated that the technologies are well understood and the technical risks are minimal.

Developing the advanced technology for a civil transport aircraft is just one part of a successful program. Additional requirements include the successful blending of new technology with the old, solving major financing and underwriting difficulties, lining up customers, and introducing the aircraft at the proper time and cost. This process begins with the conceptual design of the airframe or engine and ends with the decision to produce the aircraft.

The process by which new technology is transferred into an airframe or engine design is not well understood. Consequently, NASA funded a three-part study to gain insight into the corporate decision-making process used to develop and acquire a new or derivative civil transport. This report encompasses one part of the study. Its objective is to explore the process by which new technology is introduced into civil transports by airframe and engine manufacturers. Other contractors are studying the problem from the point of view of the airlines and from the market viewpoint using econometric forecasting. Battelle's study of the technology development process is based on a review of current technical literature, interviews with key personnel in major airframe and engine manufacturers, and an analysis of the decision interactions in the development cycles of both civil transport aircraft and engines.

Before the results of this analysis are described, it is advisable to briefly review the recent history of engine and airframe development and of the development process from which these equipments evolve. Consequently, the body of this report is organized into the following sections.

- A brief historical description of the development of the high-bypass-ratio engines and wide-body transports.
- An overview of the generic development stages required for engine and airframe development.
- A description of the analysis process used to identify the people who influence the decisions at various stages of commercial air transport development, and the barriers, real or imaginary, that must be overcome in adopting new technology.
- Description of factors that affect the jet engine and airframe development processes.
- A brief description of future commercial jet engine and airframe development.
- An overview of NASA's aircraft energy efficiency program
- Conclusions.

REVIEW OF RECENT COMMERCIAL JET ENGINE AND AIRFRAME DEVELOPMENT

The past twenty years have seen the evolution of commercial aircraft from the introduction of the then modern B-707, DC-8, and Convair 880/990 series of transports powered by axial flow jet engines to the world-wide operation of wide-bodied B-747, DC-10, L-1011, and A-300 airframes powered by large high-bypass-ratio turbofans. While the study is primarily concerned with the factors that influence the development process for such aircraft, the following brief historical reviews of their evolution helps to place the development process into context with respect to the introduction of specific engines and airframes.

Recent Engine Developments for Large Civil Transport Aircraft

High-Bypass-Ratio Engines

In 1961 both Pratt & Whitney Aircraft (P&WA) and General Electric (GE) embarked on company-funded development programs for advanced turbine engine cores; P&WA with a lightweight gas generator and GE with its GE1 "building block". As part of that effort, feasibility studies were conducted to establish the design of a new turbofan engine which would offer major technological advances over the turbofans then in-service or going into service. Design goals included reduced fuel consumption, improved noise levels, simpler construction for easy disassembly, reduced engine length, and growth capabilities to meet future airline requirements. In order to establish reasonable preliminary design goals, studies were made of thrust-weight ratio progress, specific fuel consumption progress, pressure ratio, and turbine inlet temperature increases that might be technically feasible.

Concurrently, P&WA was also performing preliminary design studies of its Advanced Technology Engine. In 1962, the first layout for an advanced technology engine was completed and company funds were committed for construction of two engines in the following year. On April 30, 1964 the first experimental engine (the STF200) was run at 31,000 lb-thrust, and 2:1 bypass ratio.(1)*

Meanwhile, GE was promoting the GE1 which could be used in conjunction with a variety of "add-on" component arrangements to produce propulsion systems tailored directly to the needs of individual aircraft designs. The high-bypass-ratio variant of the GE1 series was the GE1/6 which was conceived, designed, built and test-run within an eight month period in 1964.

The ultimate connection between these various engine developments was the USAF draft CX-4 requirement which subsequently became the CX-HLS (Experimental Cargo: Heavy Logistics System) - the C-5A. Its propulsion requirements were for high take-off thrust and low cruise SFC, implying a high-bypass-ratio turbofan. The C-5A competition was to prove highly significant for both P&WA and GE.

In order to satisfy USAF requirements, both P&WA and GE considered higher bypass ratios than proposed in their respective phase zero proposals. At this point, a key decision was made by the P&WA division leader; viz. their C-5A engine proposal would not use an air-cooled turbine rotor! As a result, P&WA entered its 40,000 lb-thrust, 3.4:1 bypass ratio JTF14E-a derivative of the STF200. GE, on the other hand, took the technological gamble and proposed a two-thirds scale of the GE1/6 (the TF39) which used an air-cooled high pressure turbine rotor. The increased turbine inlet temperature, achieved only with turbine cooling, was sufficient to demonstrate GE's unique 1 1/2 stage 8:1 bypass ratio turbofan.

In August 1965, GE was awarded a $459 million contract to develop and supply the 41,000 lb-thrust TF39 for the C-5A; 258 engines were to be produced.(1) Thus, on the strength of a U.S. government-funded program, GE was able to enter the commercial engine market at a decisive moment in air transport development.

Later in 1965, P&WA purchased the two JTF14E demonstrators from the USAF and continued with a company-funded test program.(1) The decision to use these engines in further developing the technology and

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* References are given at the end of this report.

components that would be required for commercial versions of the powerplant was made by United Aircraft Corporate management. However, it was P&WA division management that insisted on an air-cooled turbine rotor for the commercial engine. During the latter months of 1965, P&WA engineers were meeting with the technical staffs of those airlines that had expressed an interest in large transport aircraft. The objective of these discussions was to define the engine performance requirements for these aircraft. Simultaneous discussions were held with Boeing and Douglas, the two losing contestants in the C-5A airframe competition. As a result of these inputs and the STF200 and JTF14E experience, the JT9D-1 was developed with a 5:1 bypass-ratio and provided 41,000 lb-thrust. Unlike, the JTF14E, the JT9D-1 was sized to meet cruise thrust requirements rather than take-off requirements. The first two rows of turbine vanes and the first two of turbine blades in the JT9D are air-cooled. For the first time in a commercial engine, P&WA used variable stators on the high-pressure compressor. Furthermore, engine complexity was greatly reduced by eliminating 3 of the 7 engine bearings common to engines than in-service. The JT9D-1 was chosen in 1966 by Pan American to power their Boeing 747s.

The 747 had initially been based on using JT9D-1 engines rated at 41,000 lb with growth capacity to 42,000 lb. The JT9D-3 would eventually become available at 43,500 lb. However, because of airplane weight problems, delivery schedules, and cash flow problems, the engine certification schedule had to be compressed. As a result of this shortened engine development time, the early 747s experienced severe engine problems.

Meanwhile, GE was apparently intent on offering a virtually identical version of the military TF39, the CTF39, for the Boeing 747 program. However, the TF39's performance specifications were not suitable for commercial application. In reportedly finishing a poor third among the three engines proposed for the 747, the CTF39 was apparently severely penalized for the following reasons: excessive noise emission, and excessive thrust lapse rate.(2) In order to overcome these difficulties, GE announced the endorsement and commitment of corporate funding for the development of the new CF6/34 turbofan in September, 1967.(3)

The CF6-6, a two shaft turbofan derived from the TF39, first ran on October 31, 1968. Following a series of successful factory and outdoor tests, the engine was released for production in February 1969. The CF6-6 was certified in mid-1970, entering airline service in August 1971. It is available in 40,000, 41,000, and 43,000 lb-thrust versions. An uprated derivative of the CF6-6, the CF6-50, is undoubtedly GE's most important commercial engine. By designing the original series of turbofans to facilitate introduction of core-engine booster stages and other component changes, GE was able to step ahead of the competing P&WA JT9D and Rolls-Royce RB.211 to produce an engine in the 50,000 lb bracket. The CF6-50 is now being flown on DC-10-30s, 747-300s, and A300s. It entered service as the CF6-50A at a 49,000 lb-thrust rating. Growth versions are expected up to 60,000 lb-thrust by incorporating a larger fan.

GE estimates that it cost $500 million for them to get back into the commercial engine business with the CF6--even with the TF39 base. This includes engine development, production and worldwide product support facilities. Furthermore, GE must pay the U.S. government a royalty on each CF6 engine sold.

High-bypass-ratio turbofan engines were introduced into commercial service in January, 1970. The first was P&WA's JT9D on a Pan American 747 followed by GE's CF6 on an American Airline DC-10 in August, 1971 and finally Rolls-Royce's RB.211 on an Eastern Airlines L-1011 in April, 1972.(1) During the past six years, P&WA has been sued by Boeing over JT9D stiffness problems; the CF6 has suffered cracking of its C sump and bird ingestion problems, and the disintegration of fan discs forced Rolls-Royce to modify its disc design and introduce a new material specification. The cost of developing these high-bypass-ratio engines has caused financial problems for all three manufacturers, even forcing Rolls-Royce into receivership. It is little wonder that the engine companies were unwilling to undertake the next engine development program - the ten-ton engine - on a single company basis.

The Ten-Ton Turbofans

In November, 1971 General Electric and Snecma agreed to jointly develop a new ten-ton (20,000 lb-thrust class) turbofan engine, the CFM56. Two and one-half years later, on June 20, 1974, the first engine was tested.(4) Present plans are to certify the engine at 24,000 lb-thrust by the end of 1978, but to offer the engine initially at only 22,000 lb-thrust. Within six years of introduction, the CFM56 should be available in growth versions up to 27,000 lb-thrust.(5)

Since GE's F101 military turbofan is providing the core engine for the CFM56, U.S. governmental approvals had to be obtained prior to exporting this technology to France. Furthermore, GE must pay a royalty to the U.S. government on every CFM56 sold. Even with the F101 technology base, total CFM56 development costs, exclusive of production investment, are estimated at $500 million.(5) These costs will be shared equally by GE and Snecma; although, GE's portion is self-funded, whereas Snecma's support comes from French government loans. GE does not expect to break even on the program until ten years after introduction.

GE is responsible for the gas generator, the main fuel control, and system design integration. Snecma will provide the low-pressure (l-p) system, the reverser system, and engine installation.

The CFM56 has been designed for low specific fuel consumption, low noise levels, and simple maintenance. Results from NASA research activities in noise reduction have been used in selecting fan blade characteristics, such as tip speed, blade spacing, and blade profile. NASA's clean-combustor program is providing data to be used in satisfying future emission requirements. GE is paying particular attention to problem areas that occurred during the introduction of the CF6. Two specific items are tolerance control and secondary flow seals.

Preliminary design of Pratt & Whitney Aircraft's company-funded JT10D-1 dates back to October, 1971. At that time, the engine was being designed to satisfy USAF requirements for the AMST (Advanced Medium STOL Transport). However, P&WA soon thought that there would be a much bigger demand for this size engine in the commercial market. In order to insure penetration of European markets and alleviate the development cost burden, P&WA announced development of the JT10D-2 in collaboration with MTU and Fiat in May, 1973. To that point, P&WA had invested approximately $40 million in the engine and needed an estimated $200-300 million investment capital to produce the engines.(6) A fourth partner, Rolls-Royce, is being added to the consortium; although their participation had to be approved by the U.S. Justice Department, after considering U.S. anti-trust laws. However, since P&WA did not utilize military engine technology directly, export of the JT10D was not investigated by either the Defense or State Departments to the extent the CFM56 was. Understandably then, without a previous technology base, total development costs of the JT10D could approach $1000 million.(7) Certification is currently planned for late 1979. P&WA will maintain overall program control, provide the gas generator, and be responsible for engine/aircraft integration. R-R will provide the fan, the diffuser, the combustion system, and the first stage nozzle guide vane. MTU is designing the 1-p turbine while Fiat will provide the accessory gear box and other external parts.

As the two ten-ton engines continue development, there is still no firm application, civil or military. Proposals to re-engine existing 707s and DC-8s with ten-ton turbofans are being rejected by the airlines because of the estimated $9 million cost per aircraft. Nevertheless, both GE and P&WA believe that the new engines must be developed long before specific airframes because of the longer engine development lead times.

Both GE and P&WA are maintaining control over the engine core development in their respective programs. Fan, low-pressure turbine, casing, and accessories are being developed by their foreign partners. If engine corsortia continue to be the rule in the future and U.S. companies maintain primary control of the engine core, NASA should concentrate their research efforts on core-related technologies.

Review of Recent Airframe Developments for Large Civil Transport Aircraft

Intercontinental Wide Body Transports

As discussed in the review of high-bypass-ratio engines, the USAF in the mid-1960's supported study contracts and held a competition to build a large military cargo aircraft. These studies and development programs provided the technical base for the development of the wide-body civil transports for each of the companies. Boeing was the first to attempt to capitalize on this knowledge when it formed a Preliminary Design team in August 1965, even before the military contract had been awarded, to design a very large intercontinental range, commercial transport. Subsequently, Lockheed offered commercial versions of the C-5 and Douglas offered a commercial version of its proposed large military transport to the airlines.(8)

In the first round of presentations, Boeing offered to the airlines several versions of a mid-winged, double-decked, double-lobed fuselage configuration which had gross weights ranging between 532,000 lb and 599,400 lb. This configuration was rejected by the airlines and by January 1966, Boeing was showing the B-747 as a low-winged, four-engined aircraft with a large circular fuselage and having gross weights between 625,000 and 675,000 lb. The aircraft would incorporate the latest advances in wing aerodynamics and high-lift technology. It would also utilize the JT9D high by-pass engine being developed concurrently by Pratt & Whitney.(9) This time the airlines reacted favorably to the design and in March 1966, the Board of Directors of Boeing gave tentative approval for the project pending the receipt of orders for 50 aircraft. The dollar value of this order would be $1 billion or the estimated cost of the development of the aircraft. In April 1966, Pan American ordered 25 aircraft for delivery in the fall of 1969. By August 1966, Boeing had 56 orders and the B-747 was an official project.(8)

Boeing had committed to a $1 billion program using private venture capital. Part of this investment was the construction of a completely new production line from the ground up. The B-747 production facility was built at a cost of $250 million. The decision was made at the height of the airlines earning power and forecasts for future passenger volume were very promising. The program proceeded, but not without some problems.

In 1967, during the detailed design stage, it became apparent that the aircraft would exceed its weight design goal of 680,000 lb and have to be increased to 710,000 lb.(9) A Task Force was organized to review the design and offer suggestions to improve the existing design. This effort was considered to be an internal design competition by the original design team. After a review of the findings presented by the Task Force and the original design team, the original design team was allowed to continue, but with an emphasis on saving weight. They were able to reduce the weight of the aircraft 1) by careful redesign of major wing components, 2) by substituting Nomex, a composite material, for aluminum in the wing-fuselage fairings, 3) by using titanium rather than steel in some of the major load-carrying members such as the landing gear, and 4) by weight-conscious design in secondary structures.(8) In spite of all these efforts, Boeing had to revise its thrust requirements from 41,000 lb per engine to 43,500 lb. This was a higher thrust engine than originally planned for by Pratt & Whitney, and eventually led to operational problems with the engine in the early B&747's because the engines had to be developed faster than originally anticipated.(9)

By mid-1967, the production facility was complete and assembly of the first aircraft began. Roll-out of the first aircraft occurred on September 30, 1968, just two years after the production authorization was issued. The first test flight occurred on February 9, 1969, and the aircraft was certified in December 1969. The first commercial flight was on January 21, 1970.(9)

In addition to the successful development of a very large commercial transport (more than twice the size of previous aircraft) using only private venture capital, the B-747 program incorporated several highly innovative manufacturing operations. Tape-driven numerically-controlled milling machines were used to cut large billets of aluminum to intricately-designed wing and fuselage parts. The wings were lofted (the airfoil sections drawn) by computerized methods which permitted the successful assembly on the production line of components fabricated by several vendors in various parts of the country. A 5-axis German-made milling machine speeded up the manufacturing of large complex shapes. And finally, metal bonding was used to replace conventional riveting and welding of several components. This process improved the strength to weight ratio and reduced the weight of these components and, in some instances, reduced drag by providing a rivet-free, smooth surface.(8)

Medium Range Wide Body Transports

The immediate success of the jet transport and the promise of ever-increasing passenger volume caused the domestic airlines to consider the need for a medium range wide-body passenger aircraft in the mid-1960's. This was formalized by American Airlines who issued an RFP in April 1966 for a 220/230 passenger, 1850-n.mi.-range aircraft. After several iterations by Lockheed and Douglas, the aircraft evolved into a 250 passenger, 2500 n.mi. range, trijet. In February 1968, American Airlines placed an order for 30 Douglas DC-10's equipped with GE CF-6 engines.(10) Based on market surveys and the anticipated heavy demand for such aircraft, Lockheed and its engine partner, Rolls-Royce, committed to build its version, the L-1011, in March 1968.(11)

The decision by American Airlines to buy the DC-10 was made mostly on nontechnical reasons. Both aircraft for all practical purposes were identical. Their physical dimensions, seating capacity, range, cruise speed, etc., were almost exactly the same. After American made the initial purchase, other airlines who played a role in the evaluation of the designs placed their orders: TWA, Eastern, and Delta purchased the Lockheed 1011's and United opted for DC-10's.(10)

These wide-body transports brought a new level of comfort to the passenger and gave the airlines a potentially highly economic and highly profitable vehicle for transporting people and cargo. However, the anticipated passenger volume failed to materialize. Now several airlines are burdened with over-capacity and these aircraft have placed economic burdens on them because of their high acquisition costs.

COMMERCIAL TRANSPORT AIRCRAFT DEVELOPMENT PROCESS

As indicated in the preceding sections, the development of a commercial transport is a lengthy and expensive process, typically requiring 12-15 years from conception to the first operational flight. The generic design and development cycles for both engines and airframes are illustrated in Figure 1. It is, in reality, a 2-step process; the first part being the development of the propulsion system. This element of the process requires the full 12-15 years, and at current estimates, can cost more than $1 billion. The airframe development usually requires 5-7 years, and commences after the appropriate engine technology is demonstrated. Current costs, not including engines, for the development of a new transport are estimated at more than $2 billion, and for derivative aircraft at $100 and $750 million, depending on the number and magnitude of changes to be made to the basic aircraft. The development cycles for the engines and airframes are discussed briefly in the following sections.

The Engine Development Process

The development of modern aircraft engines can be a 15 year process from initial concept through introduction to service. In order to structure technological research programs which have a high probability of implementation, it is necessary to understand the engine development process, its timing, and key decision points. A thorough understanding of the process can also aid NASA in determining how far to sponsor technological programs.

Long range planning requirements for aircraft engines are based on 20-year market projections within both civil and military sectors. From these market forecasts, system requirements are defined which provide the input to preliminary design teams. Their outputs are used in developing 10-year business plans for the manufacturers.

After marketing and planning studies have defined the requirements for a new engine, there are four stages in the design and development cycle that lead to production. They are

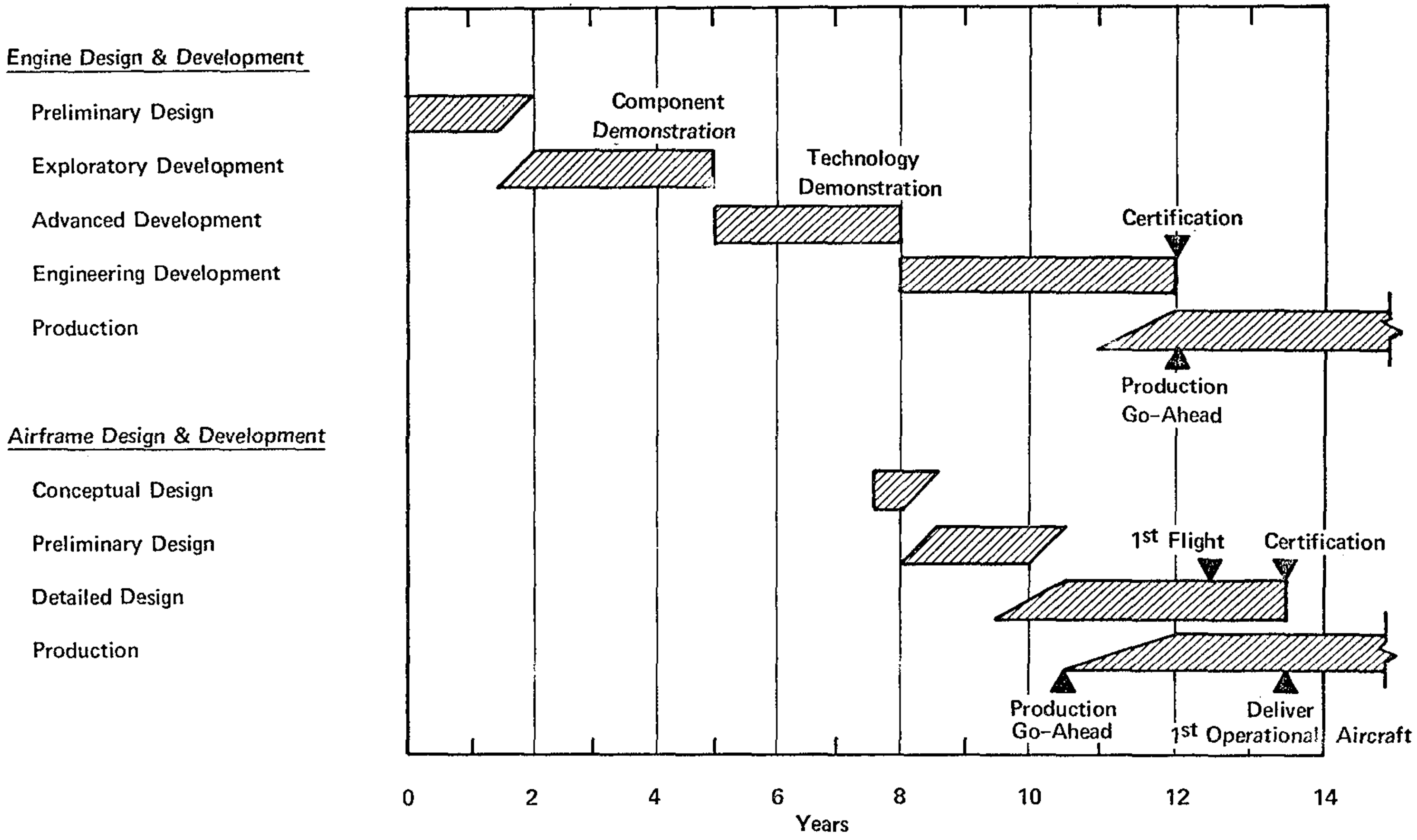

FIGURE 1. THE COMMERCIAL AIRCRAFT DESIGN AND DEVELOPMENT PROCESS

(1) The Preliminary Design stage during which engineering studies, based on the marketing inputs, of possible engine configurations are made.

(2) The Exploratory Development stage during which the validity of advanced concepts and new technologies for components are demonstrated.

(3) The Advanced Development stage during which the components for a proposed engine are assembled and tested as a unit to demonstrate system capability.

(4) The Engineering Development stage during which entire prototype engine system are used to demonstrate officially established operational requirements before production.

These stages are shown in Figure 1 with a typical time scale.

The preliminary design stage is approximately an 18 to 24-month period during which engines based on different engineering concepts are sized to meet projected operational requirements. These operational requirements are based upon marketing studies that forecast aircraft requirements 15 to 20 years in the future. At this point, engine concepts are developed and their components and required new technologies are identified. Engine tradeoff analyses are performed to yield an initial definition of engine cycle, airflow size, thrust level, etc. If the concepts show promise, an exploratory development program is established to develop the necessary components and associated manufacturing technologies.

The objectives of exploratory development are to demonstrate the validity of advanced concepts and new technologies on the component level.(12) Components for the proposed engines are designed and tested to demonstrate that the components necessary for the proposed engines are feasible and can meet performance requirements. Usually there are several contenders at this point, each method having been identified as a possibility during the preliminary design phase. Engineering reviews of these programs are conducted monthly; upper management reviews then at least annually. This phase typically lasts 2 to 3 years with several options being explored. If it can be shown that the components can be developed, then the engine concepts progress to the next stage, advanced development.

During advanced development, new components are assembled and tested as a unit to investigate component interactions and total system performance. In addition to mechanical interfaces, thermodynamic and aerodynamic compatibility must be insured. The technology selected for engine qualification is generally consistent with the levels developed in technology improvement programs. Advanced engine proposals must be based upon proven concepts rather than having to prove individual components during engineering development. This stage lasts about two years, at the end of which one engine concept is selected for engineering development. Prior to the go-ahead for engineering development, a decision to commit to a new engine must be made and top management approval of the engine specifications must be obtained.

The objective of the engineering development phase is to demonstrate approved operational requirements with an entire engine system. The engine evolves to its flight configuration and tests are undertaken to certify the engine for production. During this stage, the airframe manufacturers evaluate the suitability of the engine for new or derivative aircraft designs. This stage typically corresponds in time to the beginning of the airframe design and development cycle. The engineering development stage normally lasts about 4 to 5 years, but it can be accelerated. Certifying the engine for commercial use signals the end of this stage and the start of production.

The production stage involves producing not only the engines for initial installation on the airframe, but the spares and spare parts which represent a major portion of the production run.

Airframe Development Process

The design and development cycle of the airframe manufacturers consists of four stages as follows:(13)

(1) The conceptual design stage during which the aircraft is conceived

(2) The preliminary design stage during which the layout and general configuration is defined

(3) The detailed design stage during which the design is frozen and the detailed design is completed

(4) The production phase during which the aircraft is manufactured.

As shown in Figure 1, the conceptual design stage is usually of short duration, approximately 1 to 6 months. It involves only a small staff (as few as five people) who define the basic configuration of the aircraft to meet the requirements of the probable customer. If the design potentially meets the customer's requirements and receives approval of the chiefs of advance design, the aircraft advances to the preliminary design stage.

The preliminary design stage typically lasts 18 to 24 months. However, this phase has been known to last longer, depending upon the technical difficulty of the design, the urgency of the requirement for a new airframe, and the number of compromises and iterations that must be performed to reach a satisfactory solution. Both analytical and experimental studies are conducted in this stage to resolve uncertainties in the design. Approximately 5 to 10 percent of the development cost is expended. This can amount to $50 to $100 million. In this stage of the design, there is a strong interaction with the major airlines to refine the initial requirements which were the basis of the conceptual design. Negotiations are conducted with the engine manufacturers to reach an acceptable engine performance for the airframe. After suitable trade-offs between the customer's requirements and the airframe performance are achieved, the design is reviewed for production go-ahead, and the next stage, detailed design.

The detailed design stage extends from production go-ahead through the certification of the aircraft. There is an overlap with the actual production of the aircraft because in commercial practice, the first commercial flight occurs within a month after certification. From production go-ahead to the first in-service flight typically requires 30 to 36 months for a derivative aircraft and 40 to 48 months for a new aircraft. The last 12 months are devoted to certifying the aircraft. During the peak of the detailed design stage, as many as 2,000 engineers are employed.

The production phase begins about 18 months after production go-ahead and involves first preparing the fabrication facility for production. This stage employs the largest number of people and, if the design is successful, it is the longest lasting stage of the development process. Some current aircraft have remained in production with programmed improvements for over 20 years. Typically, the production phase will last as long as the total design and development process - about 7 years.

ANALYSIS METHODOLOGY

In previous sections, it was noted that the development of commercial airframes and engines is a complex, long-term process involving a large number of decisions regarding the selection of applicable technologies. These decisions are made by people who have a variety of scientific, engineering, financial and legal backgrounds and bring a variety of viewpoints to the decision-making process. The development of an appreciation of the factors that influence decisions leading to the introduction of new technology, and of the influences that various people and organizations have in the development process, demands a detailed and highly structured investigation. Such an investigation must, however, strike a reasonable balance between the data requirements and the demands that can reasonably be requested of knowledgeable people in the commercial aircraft industry. This balance was accomplished through the development of a detailed analysis methodology prior to discussions with people in the aircraft industry, followed by documentation of findings and subsequent analyses. In this way, the interviewers were prepared to obtain the significant data with minimal imposition on the time of responsible aircraft industry executives.

The analysis methodology provides a vehicle for structuring and analyzing the factors that influence commercial airframe and engine manufacturer's decisions regarding the introduction of new technology in commercial aircraft. The implementation of this methodology involved five steps as follows:

(1) Define the generic components of the analysis framework related to decision making in the commercial airframe and jet engine industry.

(2) Define, in detail, the subelements of the generic components.

(3) Conduct interviews with key personnel in the major U.S. commercial airframe and jet engine manufacturing companies to gain understanding of their decision-making processes regarding the introduction of new technology.

(4) Document the interview information by recording interactions among the subelements of the analysis framework.

(5) Analyze the interactions of subelements of the generic components to identify: (1) the key decision influencers, and (2) the key barriers to innovation at each stage of the airframe and jet engine development process.

Generic Components of the Analysis Framework

The analysis framework was synthesized to encompass four major components. Since the objective was to develop an understanding of the factors affecting the introduction of new technology in the engine and airframe manufacturing industry, the first major component was defined to be the Design and Development Stages, through which new engines and airframes are evolved. The second component is the set of Design Criteria that is used in each Design and Development Stage. The third set of factors is the set of participants termed "Decision Influencers", that affect the design criteria. Finally, the last set of factors was defined to be Barriers to Innovation. These factors influence the Decision Influencers directly in establishing the Design Criteria and, consequently, the decisions that are made during airframe and engine development regarding the introduction of new technology.

The analysis framework is shown schematically in Figure 2. The 1's indicate the existence of interactions between:

In Matrix A--A Design and Development Stage and a Design Criterion

In Matrix B--The same Design Criterion and a Decision Influencer

In Matrix C--The Decision Influencer and a Barrier to Innovation.

Thus, it is possible to say that the indicated Barrier to Innovation interacts with the designated Design and Development Stage and similarly, that the indicated Decision Influencer affects the Design and Development Stage. These interactions may be more clearly illustrated after a few simple matrix manipulations. That is, multiplication of matrices A and B yields a matrix

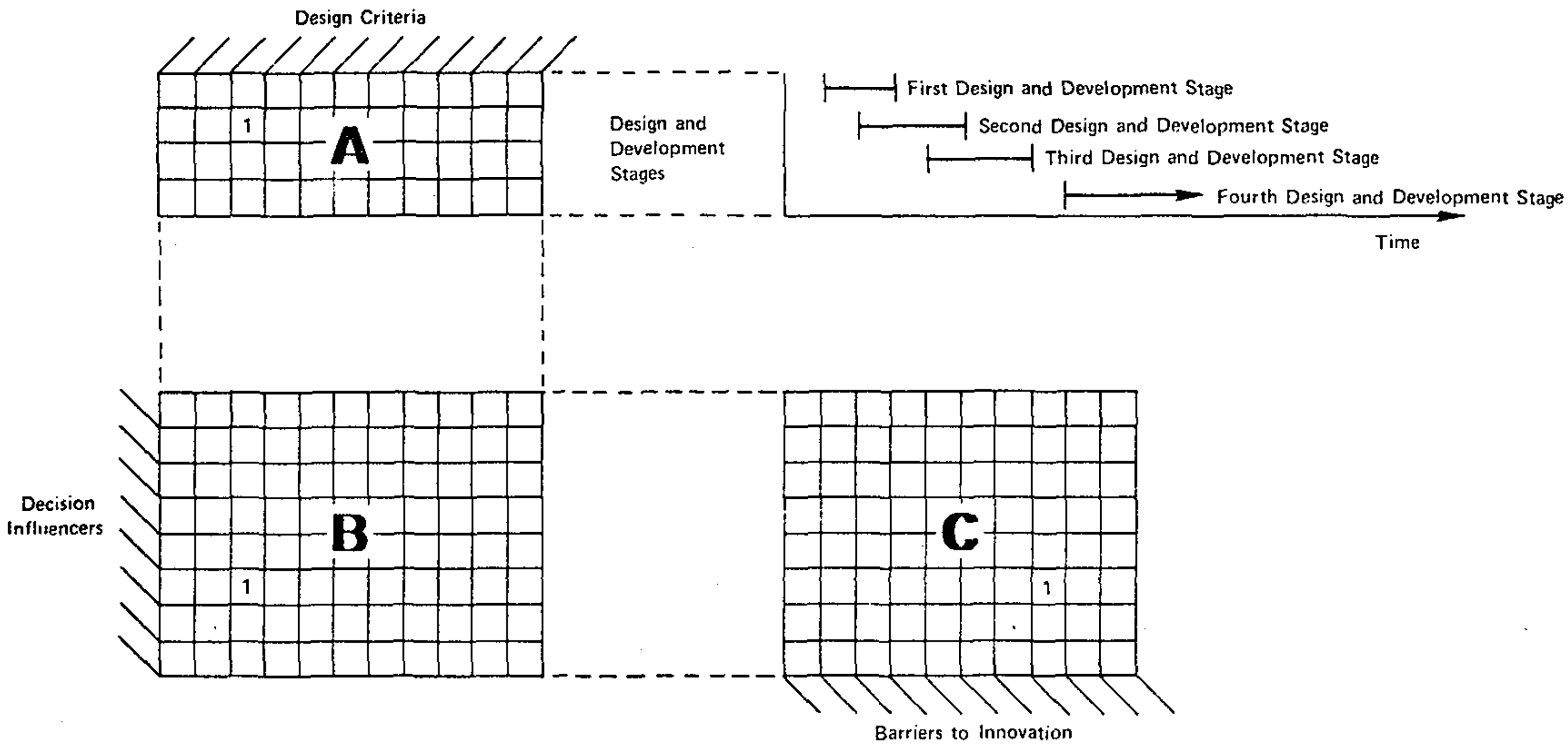

FIGURE 2. FRAMEWORK FOR STRUCTURING THE INTERACTION OF BARRIERS TO INNOVATION, DECISION INFLUENCERS, AND DESIGN CRITERIA IN AIR TRANSPORT DESIGN

directly relating Design and Development Stages to Decision Influencers. The matrix entries are then the relative level of interaction of a Decision Influencer with the corresponding design activity. Then, if we call this resultant Matrix D and multiply it by Matrix C, the resultant matrix relates the Barriers to Innovation to the Design and Development Stages. The entries in this matrix indicate the relative level of interaction that a barrier has with a corresponding design activity. We will see later how these data are aggregated to identify key Decision Influencers and Barriers to Innovation.

Subelements of the Analysis Framework Components

The second step in the development of the analysis methodology involved decomposing each of the generic components discussed above into its constituent elements. In the case of Design and Development Stages, this involved discussions with airframe and engine manufacturers to arrive at a representative set of stages for each, and then a series of design activities within each stage. The results will appear in a later matrix.

Similarly, in the case of Design Criteria, discussions with manufacturers, as well as Battelle staff, experience was used to develop separate sets of design criteria for airframe and jet engine development under the general headings of Market, Economic, and Airframe or Engine Design Criteria.

The list of Decision Influencers for the airframe and engine manufacturers are reasonably parallel. They were developed from Battelle's understanding of the agencies that influence aircraft design and our analysis of the organizational structure of the manufacturers obtained from published organization charts and through interviews with the manufacturers.

The lists of more than 50 Barriers to Innovation were generated largely from a review of literature on the process of innovation and analysis and resident familiarity with the histories of airframe and engine development. Both lists contain nearly common sets of barriers under the titles

General Technology Considerations, Economic Consideration, Social Considerations, and Management Considerations. Each list also contains a set of barriers specific to airframe or engine technology as appropriate.

Interviews With Airframe and Engine Manufacturers

During late July and early August, 1976, interviews were conducted with key personnel of the two major U.S. commercial jet engine manufacturers

- Pratt & Whitney Aircraft, East Hartford, Connecticut
- General Electric Company, Evandale, Ohio, and Lynn, Massachusetts.

Interviews were also conducted with key personnel of the three major U.S. commercial airframe manufacturers

- Boeing Commercial Aircraft Company, Renton, Washington
- Lockheed-California, Burbank, California
- Douglas Aircraft Company, Long Beach, California.

The purpose of these interviews was to obtain an improved current understanding of the airframe and engine design processes of the criteria used by the participants in the decision-making process, and of the factors that influence the introduction of new technology in the development of new energy and cost effective U.S. commercial aircraft.

Documentation of Interview Information

The interviews conducted by the Battelle staff with airframe and engine manufacturers' personnel were first documented in internal trip reports. From these reports, as well as current research papers obtained from manufacturers and other sources, an interim working paper was developed that categorizes the factors affecting future aircraft development through their impact on the various types of organizations involved. As a second documentation step, the interviewers were asked to fill out the sets of matrices corresponding to those indicated in Figure 2.* They were requested to fill in only <u>important</u> interactions and in filling out the respective airframe and engine matrices, to produce composite views of the three airframe and two engine manufacturers. Thus, Figure A-1 represents their perception of the important interactions affecting the introduction of new technology in commercial jet engines by Pratt & Whitney and General Electric. Similarly, Figure A-2 represents the Boeing, Lockheed, and Douglas composite view of the interactions among factors involved with the introduction of new technology in commercial airframes.

This method of documentation requires the interviewers to rigorously consider and make a judgment about each interaction in the complex decision process involved in the design and development of new engines and airframes. It also facilitates recording the interactions that the interviewers are most confident of, and through subsequent analysis, facilitates deriving the other interactions.

Analysis of Interactions

Figures A-1 and A-2 were designed to allow the interviewers to document interactions between Barriers to Innovation and Decision Influencers, between Decision Influencers and Design Criteria, and between Design Criteria and Design and Development Stages. Appropriate matrix multiplication results in matrices (see Appendix A, Figures A-3 through A-6) which show the interactions between

- Decision Influencers and Commercial Jet Engine Design and Development Stages
- Decision Influencers and Commercial Air Transport Design and Development Stages

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* These matrices, which contain the basic data used in the analysis of interactions are presented in Appendix A as Figures A-1 and A-2.

- Barriers to Innovation and Commercial Jet Engine Design and Development Stage
- Barriers to Innovation and Commercial Air Transport Design and Development Stages.

As indicated in Appendix A, these interactions can be analyzed to arrive at a ranking of the barriers to incorporation of new technology in future commercial transport aircraft, and also provides a mechanism for identifying the key decision influencers at various stages of development. The results of this analysis are described in the following two sections that address factors affecting the decision-making processes of manufacturers.

DESCRIPTION OF FACTORS AFFECTING THE DECISION-MAKING PROCESSES OF ENGINE AND AIRFRAME MANUFACTURERS

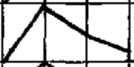
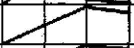
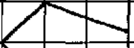
The analysis methodology presented in the preceding section is basically a scheme for systematically organizing a large body of information so that it can be analyzed to arrive at a rank ordering of importance of decision influencers at each stage of engine and airframe development, as well as a rank ordering of the barriers to incorporation of new technology in future commercial transport aircraft.

Tables 1 through 4 summarize the analytical results with regard to the importance of barriers to innovation in commercial jet engine and airframe development. The top one-half of the barriers are ranked in Tables 1 and 3 in order of descending importance for the engine and airframe development cycles, respectively. Both the airframe and jet engine industries have resolved a great many factors that are thought to be significant inhibitors to the introduction of new technology in some industries. These potentially significant barriers to innovation that have been largely overcome are listed in Tables 2 and 4 in the inverse order of importance for the jet engine and airframe industries, respectively. On the other hand, the factors listed in Tables 1 and 3 (and particularly those near the top of Tables 1 and 3) are currently significant inhibitors to the introduction of new technology, but many can be alleviated by continued conscious cooperative efforts by the aircraft industry, the airlines, and the U.S. Government.

In addition to presenting the rank ordering of the importance of barriers to innovation across all design and development stages, the first four columns of each table indicate the ranks of the barriers within the individual design and development stages involved with either commercial airframe or jet engine development. The fifth column presents these data as trend lines indicative of how the ranking varies as a development program evolves from its earliest design stage to production.

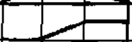
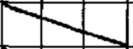
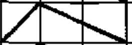
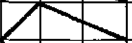
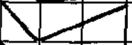
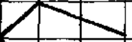
The entries in the last column indicate the source of the barrier in terms of whether it is inherent to the manufacturer's organization (i.e.,

TABLE 1. KEY BARRIERS TO INNOVATION IN COMMERCIAL JET ENGINE DEVELOPMENT
(All Design and Development Stages)

Rank Order (All Design and Development Stages)	Barriers to Innovation	Rank in Design and Development Stages: Preliminary Design	Exploratory Development	Advanced Development	Engineering Development	Trend in Rank Order Over Design and Development Stages (Each Row Independently Scaled)	Source of Barrier*
1	Cost of new technology installed in aircraft	1	4	1	1		P
2	Personal biases	3	7	5	2		E
2	Personalities of decisionmakers and willingness to take risks	3	7	5	2		E
2	Company traditions/personalities	3	7	5	2		E
5	Lack of competition from other manufacturers in the use of new technology	7	14	11	7		P
6	Lack of trained maintenance personnel	9	12	8	5		O
6	Lack of accumulated experience base with new technology	9	12	8	5		E
8	Time required to certify new technology	15	1	2	8		C
8	Certifying the use of new technology by FAA for commercial aircraft	15	1	2	8		C
10	Lack of investment enthusiasm in a maturing industry (cash flow situation)	2	34	31	8		O
11	Time to implement technology on a production basis	17	3	4	12		P
12	Conservative designs avoiding risk (due to publicity-afforded failure) may not exploit the potential advantages of new technology	6	34	24	12		O
13	Lack of low-cost methods for composite structure fabrication and nondestructive testing	19	6	8	8		P
14	Service-time required to develop confidence for designer and customer acceptance of new technology	13	27	18	12		P/O
15	Liability considerations	8	34	32	20		O
16	Airline reluctance to use new technology	11	32	29	20		O
16	Public reaction to new technology	11	32	29	20		O
18	Integrated nacelle design	21	7	13	16		P
19	Due to the need for back-up technologies, it is difficult to exploit new technology to enable radically different vehicle configurations to be developed to reduce life-cycle costs	24	7	13	16		P
20	Turbine cooling	21	14	19	20		P
21	Foreign object impact resistance	24	20	15	16		C
21	Disc containment	24	20	15	16		C
23	Program management structure – matrix versus hierarchical	28	19	15	15		P
24	Long lifetime design requirements for commercial aircraft	34	4	12	24		P/O
25	Lack of in-service demonstration as opposed to prediction of performance	14	39	37	25		O
26	Turbine stage loading	31	20	23	25		P
27	Time at which technology is considered to be "available" is vastly different for scientists, aircraft designers, and production specialists	32	23	24	27		P

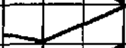
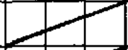
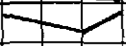
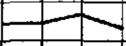
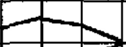
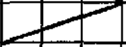
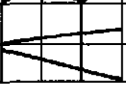
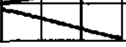
**Source of Barrier is coded as follows:*
P = Production and preceding stages of development.
C = Certification.
O = Operation.
E = Experience (tradition, preference, etc.)

TABLE 2. BARRIERS TO INNOVATION IN COMMERCIAL JET ENGINE DEVELOPMENT IN INVERSE ORDER OF IMPORTANCE

Rank Order (All Design and Development Stages)	Barriers to Innovation	Rank in Design and Development Stages				Trend in Rank Order Over Design and Development Stages (Each Row Independently Scaled)	Source of Barrier*
		Preliminary Design	Exploratory Development	Advanced Development	Engineering Development		
51	Rapid rate at which technology is changing	50	50	51	50		P
51	Lack of recognition of need for advancement	50	50	51	50		O
51	Lack of pressure from customers for more economical equipment	50	50	51	50		O
51	Nonproprietary nature of results obtained through NASA's program	50	50	51	50		P
50	Export controls (CoCom list)	50	39	47	50		P
48	Adequacy of materials supply infrastructure	48	48	44	44		P
48	Lack of training of production workers	48	48	44	44		P
46	Disposal of existing production machinery that may not be fully amortized	42	44	48	46		P
46	Lack of an identifiable production champion	42	44	48	46		P
45	The cost of tooling at all stages of manufacturing sequence using new technology	36	42	44	46		P
44	Developing confidence of suppliers and customers that new technologies are sufficiently advanced to justify the use of new materials or processes	33	50	48	46		P
43	Market uncertainty for type and quantity of new aircraft	29	44	43	42		P
39	Material characteristics	44	27	33	37		P
39	Blade manufacturability	44	27	33	37		P
39	Seal design	44	27	33	37		P
39	NIH factors	44	27	33	37		P
38	Union objections to changing technology	23	44	42	42		P
37	Cost of demonstration programs	30	42	39	31		C
34	Patent/license considerations	17	39	41	41		P
34	Difficulty in recruiting adequately trained designers, production personnel, etc., who can work with new technology	40	23	24	27		P
34	Lack of experience in production adds to uncertainty and risk	40	23	24	27		P
32	Lack of production machinery infrastructure to produce machinery for new technology	35	23	24	27		P
32	Disposal or conversion of production facilities for conventional technology	27	38	38	31		P
29	Relatively small performance savings associated with any particular component combined with the need to take incremental steps in innovative design	36	14	20	33		P
29	Bearing/rotor design	36	14	20	33		P
29	Historic design practices are favored	36	14	20	33		P
28	Financing of new production facilities when visibility is limited on aircraft procurement and rates	19	34	40	36		P

*Source of Barrier is coded as follows:
P = Production and preceding stages of development.
C = Certification.
O = Operation.
E = Experience (tradition, preference, etc.)

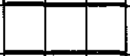
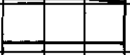
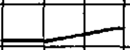
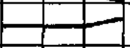
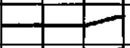
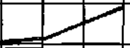
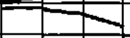
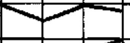
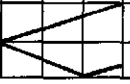
TABLE 3. KEY BARRIERS TO INNOVATION IN COMMERCIAL AIRFRAME DEVELOPMENT
(All Design and Development Stages)

Rank Order (All Design and Development Stages)	Barriers to Innovation	Rank in Design and Development Stages				Trend in Rank Order Over Design and Development Stages (Each Row Independently Scaled)	Source of Barrier*
		Conceptual Design	Preliminary Design	Detailed Design	Production		
1	Long lifetime design requirement for commercial air transports	1	1	2	2		P/O
1	Service-time required to develop confidence for designer and customer acceptance of new technology	2	2	1	1		P/O
3	Liability considerations	6	4	3	7		O
4	Certifying the use of new technology by FAA for commercial aircraft	4	3	5	9		C
4	Cost of demonstration programs	5	6	4	6		C
6	Company traditions/personalities	7	7	7	2		E
7	Execessive qualification testing and proof testing	3	5	9	26		C
8	Lack of investment enthusiasm in a maturing industry (cash flow situation)	8	11	5	2		O
9	Market uncertainty for type and quantity of new aircraft	9	12	11	5		P
10	Lack of competition from other manufacturers in the use of new technology	10	10	8	9		P
10	Historic design practices are favored	11	8	9	8		P
12	Lack of demonstrated hardware reliability	11	9	14	13		O
13	Time at which technology is considered "available" is vastly different for scientists, aircraft designers, and production specialists	15	13	12	9		P
13	Developing confidence of suppliers and customers that new technologies are sufficiently advanced to justify the use of new material or processes	15	13	12	9		P
15	Cost of new technology installed in aircraft	13	16	16	13		P
16	Due to the need for back-up technologies, it is difficult to exploit new technology to enable radically different vehicle configurations to be developed to reduce life-cycle cost	17	17	15	15		P
17	Lack of accumulated experience base with new technology	14	13	24	27		E
18	Repair or replacement of composite structures after accident (e.g., fire)	18	19	20	18		O
19	Rapid rate at which technology is changing	19	19	17	20		P
19	Lack of experience in production adds to uncertainty and risk	19	19	17	20		P
21	Lack of low-cost methods for composite structure fabrication and nondestructive testing	21	18	20	25		P
22	Personal biases	23	22	17	15		E
23	Personalities of decisionmakers and willingness to take risks	25	23	20	15		E
24	Lack of in-service demonstration as opposed to prediction of performance	26	24	26	20		O
25	Lack of identifiable product champion	27	26	25	24		P
26	Development of system design requirements	23	25	28	30		P

*Source of Barrier is coded as follows:
P = Production and preceding stages of development.
C = Certification.
O = Operation.
E = Experience (tradition, preference, etc.)

FOLDOUT FRAME 1

TABLE 4. BARRIERS TO INNOVATION IN COMMERCIAL AIRFRAME DEVELOPMENT IN INVERSE ORDER OF IMPORTANCE

Rank Order (All Design and Development Stages)	Barriers to Innovation	Rank in Design and Development Stages				Trend in Rank Order Over Design and Development Stages (Each Row Independently Scaled)	Source of Barrier*
		Conceptual Design	Preliminary Design	Detailed Design	Production		
50	Nonproprietary nature of results obtained through NASA's program	50	50	50	50		P
50	Lack of pressure from customers for more economical equipment	50	50	50	50		O
50	Program management structure — matrix versus hierarchical	50	50	50	50		P
49	Export controls (CoCom list)	49	49	49	49		P
48	Relatively small performance savings associated with any particular component combined with the need to take incremental steps in innovative design	48	48	48	48		P
47	Public reaction to new technology	47	47	47	45		O
46	Improved preliminary design weight estimate and payoff methods	46	46	46	47		P
44	Patent/license considerations	44	43	45	45		P
44	Disposal of existing production machinery that may not be fully amortized	45	45	43	41		P
43	Lack of recognition of need for advancement	43	43	44	41		O
42	Cost of establishing property matrix of composite materials	42	42	42	44		P
41	Developing low-cost methods for fabricating high-quality composite structures	41	41	41	41		P
40	Time to implement technology on a production basis	37	37	40	40		P
37	The cost of tooling at all stages of manufacturing sequence using new technology	37	37	36	32		P
37	Lack of production machinery infrastructure to produce machinery for new technology	37	37	36	32		P
37	Adequacy of materials supply infrastructure	37	37	36	32		P
36	Difficulty in recruiting adequately trained designers, production personnel, etc., who can work with new technology	36	36	33	31		P
35	Lack of trained maintenance personnel	32	35	36	37		O
33	Direct substitution of parts (composites for metals) does not allow opportunity in design to exploit advantageous characteristics of composites	33	33	34	32		P
33	Conservative designs avoiding risk (due to publicity afforded failure) may not exploit the potential advantages of new technology	33	33	34	32		O
32	Financing of new production facilities when visibility is limited on aircraft procurements and rates	33	32	27	20		P
30	Interface of composites with metallic structures (e.g., complex, costly joints)	29	29	31	38		P/O
30	Development of advanced design and manufacturing technologies for large airframe structures to reduce number of joints and fasteners and hence, part count	29	29	31	38		P
29	NIH factors	28	31	28	29		P
28	Disposal or conversion of production facilities for conventional technology	31	27	23	18		P
27	Airline reluctance to use new technology	22	27	30	27		O

*Source of Barrier is coded as follows:
P = Production and preceding stages of development.
C = Certification.
O = Operation.
E = Experience (tradition, preference, etc.)

FOLDOUT FRAME 2

Production), to the airlines (i.e., Operation), to the certification process, or to factors related to historical precedence and tradition (i.e., Experience). This type of classification facilitates some general comments about the barriers and where action might be directed to reduce them. It is worth noting, for example, that all but one of the engine and airframe certification- or experience-related barriers fall in Tables 1 (Engines) and 3 (Airframes). That is, they are in the top half of the barriers when ranked in order of decreasing importance. Clearly, the uncertainties, time, and costs associated with certifying equipment using new technology are a matter of concern to the engine and airframe manufacturers.

The experience-related barriers result from traditions and preferences exhibited by both the manufacturers and airlines. The manufacturers tend to maintain design techniques and materials usages across generations of aircraft--often for very legitimate reasons in terms of design and production staff capability, and in terms of marketing aircraft with which the operators can identify. The airlines do not have any particular enchantment with the introduction of new technology with which they may have little familiarity and confidence, and which may result in only incremental improvement on their return on investment over that obtained with current designs.

It is also apparent from an examination of the last column in Tables 2 (Engines) and 4 (Airframes) that the majority of the potentially less critical barriers originate with manufacturers, and to a lesser extent, with the airlines. The fact that these barriers are of low rank relative to those that appear in Tables 1 and 3 is interpreted to mean that the manufacturers and airlines have taken actions and developed programs to reduce their potentially negative effect on the introduction of new technology in airframe and engine development.

Inspection of the last column in Tables 1 through 4 reveals that the large majority of barriers to innovation originate with the engine and airframe manufacturers, either directly or indirectly through their perception of the business environment within which they operate. While many of these barriers have been overcome, the last column in Tables 1 and 3 indicate that approximately one-half of the important barriers originate with the manufacturers.

These barriers cover a wide range of topics ranging from market uncertainty for the type of aircraft required, to technical factors such as the need to carry through parallel designs with conventional technology as a backup should the new technology designs not prove feasible. These topics are not easily categorized, though most are associated in one way or another with the costs, time and risk factors associated with introducing new technology.

Influences on Engine Development

A detailed examination of Tables 1 and 2 results in an interesting profile of the jet engine manufacturers which is quite different from that of the airframe manufacturers. The engine manufacturers are first and foremost concerned with the cost of new technology installed in the aircraft. The manufacturer's primary concern is that new technology should result in reduced life-cycle costs to the user. Today, the user usually has a choice of several engines for any given airframe and base their choice on life-cycle costs. To take the step of introducing new technology, the engine manufacturers must be convinced that new technology will be cost effective over the life of the airframe. This is, of course, very difficult to accomplish and, consequently, acts as a barrier to the introduction of new technology.

The barriers ranked 2 through 6 are indicative of the conservative nature of the engine manufacturers, their long experience in the engine field, and concern for the reputation of their companies as reflected by the quality of the products they produce.

The next four barriers in Table 1 reflect the engine manufacturers' concern for proper timing of their developments. In general, the timing uncertainties that result when new technology is incorporated in an engine create a barrier to the introduction of technology.

Probably due to the long development time for jet engines and the ultimately higher production total of engines as compared to airframes, the engine manufacturers tend to view technical items, and service and warranty factors as less significant than do the airframe manufacturers. The development of technical items is a nonrecurring cost in the engine development process and can be amortized over the entire production run of the original equipment engines and replacement engines. Service and warranty factors are considered to be less critical because of the long development effort afforded engines and the manufacturers' resultant confidence in their products.

In general, the engine manufacturers are well aware of barriers to innovation and have taken steps to alleviate them. Each of the barriers identified in Table 1 are commented on in Table 5 with respect to the steps that the engine manufacturers have, or are, taking to alleviate them. As discussed in Table 5, the engine manufacturers use two major mechanisms for reducing the production-related barriers to introducing new engine technology. These mechanisms are:

(1) Product improvement programs used to develop technology for current engines.

(2) Advanced technology programs aimed at the development of new engines.

In accomplishing these programs, the manufacturers have evolved organizational structures and procedures in direct response to some of the key barriers listed in Table 5. For example, they:

(1) Utilize a matrix organization of multidisciplinary project teams to explore several alternative technologies in the course of developing satisfactory improved components or new engine concepts.

(2) Use experienced development engineers to take concepts generated in preliminary design and develop them into production-line items with a minimum of delays. In addition, teams of R&D specialists, designers, production specialists, and maintenance specialists are brought together to develop new concepts, such as low-cost fabrication techniques, nondestructive inspection procedures, and engine diagnostic techniques.

To demonstrate to airframe manufacturers and airlines that new technologies are ready for implementation, the engine manufacturers conduct extensive ground tests and demonstrations of newly developed engines or components.

TABLE 5. KEY BARRIERS TO INNOVATION AND INTERACTIONS WITH MANUFACTURERS' PROGRAMS

(COMMERCIAL JET ENGINE DEVELOPMENT)

Rank Order	Barriers to Innovation	Interaction With Manufacturers' Programs
1	Cost of new technology installed in aircraft	The manufacturers must demonstrate to the airlines that new technologies are available at lower cost on a life-cycle cost basis than current technology.
2a	Personal biases	The stability and service organization of U.S. engine manufacturers accompanied by an excellent product and good management practice has resulted in world leadership in this area. The manufacturers must evaluate new technology options early in the development process and make comparisons with proven technologies on an objective technical and economic basis.
2b	Personalities of decisionmakers and willingness to take risks	
2c	Company traditions/personalities	
5	Lack of competition from other manufacturers in the use of new technology	The competition to correctly time the introduction of a new design is the critical competitive factor. Only a limited amount of new technology is likely to be introduced in a new design because of the conservative nature of the few companies involved and the large investment risked in the development of a new engine.
6a	Lack of trained maintenance personnel	Manufacturers have developed information dissemination programs to educate airline maintenance personnel on maintenance and repair procedures for new materials and new equipment.
6b	Lack of accumulated experience base with new technology	Manufacturers require supportive funds to gain experience with new technologies. They obtain these funds both from Government contracts and in-house funds from profits. Historically, military experience has contributed significantly to commercial jet engine development.
8a	Time required to certify new technology	The engine manufacturers have developed real-time digital computer methods to reduce the time required to analyze certification test data. They also are studying methods to cause simulated failures rather than destructively test engines to certify them as safe.
8b	Certifying the use of new technology by FAA for commercial aircraft	Engine manufacturers must continually keep FAA aware of the latest advances in new technology applications to avoid extended delays in receiving FAA approvals for its use.

TABLE 5. (Continued)

Rank Order	Barriers to Innovation	Interaction With Manufacturers' Programs
10	Lack of investment enthusiasm in a maturing industry (cash flow situation)	The lack of investment in the aircraft industry is caused by the current financial condition of the airlines. Potentially, technical developments such as improved engine components and an energy-efficient engine should result in long-term economic benefits to the airlines.
11	Time to implement technology on a production basis	Engine manufacturers assign older engineers to develop ideas conceived by younger analysts because they have the design and production experience to reduce the time required for new technology to reach production.
12	Conservative designs avoiding risk (due to publicity-afforded failure) may not exploit the potential advantages of new technology.	Engine manufacturers have a reputation for being conservative. However, because of inherently long development cycles for new engines, they usually have orderly procedures to examine every aspect of a new technology before committing it to a production engine.
13	Lack of low-cost methods for composite structure fabrication and nondestructive testing.	Manufacturers have teams of scientists, designers, production and maintenance specialists assigned to the development of low-cost, competitive methods for fabrication and NDT of modular engine components.
14	Service-time required to develop confidence for designer and customer acceptance of new technology.	Manufacturers have in-house programs to develop new engine technologies and to obtain static test experience on critical components. However, more extensive demonstrations are needed to develop customer acceptance of new technology.
15	Liability considerations	New interpretations of product liability laws have caused manufacturers to become very cautious about the introduction of new technology into civil transport engines.
16a	Airline reluctance to use new technology	Manufacturers have new engine development programs for derivative aircraft which the airlines are reluctant to accept. This reluctance is based on problems encountered with introduction of the first generation of high by-pass ratio engines.
16b	Public reaction to new technology	Where the technology is apparent to the public, the airlines are reluctant to introduce a new technology because of possible negative public reaction. The potentially energy efficient turboprop engine may fall in this category.
18	Integrated nacelle design	Manufacturers have in-house studies related to integrated nacelle design for CTOL aircraft engines.
19	Due to the need for back-up technologies, it is difficult to exploit new technology to enable radically different vehicle configurations to be developed to reduce life-cycle costs.	During the development of a radically new engine, several alternative technologies are studied and evaluated until the technology demonstration phase of exploratory development. At this time, the most promising technologies are selected for development. For example, in the development of the J-79 engine, three methods for controlling the airflow into the compressors were evaluated.

TABLE 5. (Continued)

Rank Order	Barriers to Innovation	Interaction With Manufacturers' Programs
20	Turbine cooling	The manufacturers are investigating methods for improving film cooling and for making transpiration cooling practical for turbine blade cooling. They are also developing matrix materials to increase their resistance to the high temperature environment of engine turbines.
21a	Foreign object impact resistance	This is a problem for all engines. The engine manufacturers have investigated several techniques to save weight in turbofan engines by introducing composite fan blades. However, they have not yet devised a composite fan blade to withstand foreign object damage tests.
21b	Disc containment	Manufacturers have the disc containment in hand with conventional technology. However, attempts to reduce the weight with new materials while maintaining the same level of integrity are required.
23	Program management structure--matrix versus hierarchical	Engine manufacturers use project teams in a matrix organization to study technology options before committing to the development of a new engine. They feel that the matrix type of organization is most appropriate for managing engine development programs.
24	Long lifetime design requirements for commercial aircraft	Engine manufacturers warranty hot parts of the engine for at least 2,500 hours and cold parts up to 30,000 hours. The disc of JT9D has a service life of 15,000 cycles/25,000 hours. Manufacturers have product improvement programs to extend component life or improve performance based on airline in-service reports.
25	Lack of in-service demonstration as opposed to prediction of performance	Manufacturers are developing improved engine monitoring and diagnostic techniques to obtain information needed to minimize engine performance degradation.
26	Turbine stage loading	The development of a new engine requires the analysis of single stage versus multi-stage turbines for maximum work efficiency. This trade-off is made in the preliminary design phase of engine development.
27	Time at which technology is considered to be "available" is vastly different for scientists, aircraft designers, and production specialists.	Manufacturers have formed teams consisting of scientists, designers, and production specialists to accelerate the acceptance of a new technology for production.

The traditions and biases that develop in mature organizations frequently become barriers to innovation. They are addressed by the engine manufacturers through multiple development programs and efforts are made to sell the new technology when it appears to be more profitable than old technology. Also, they have in-house or contracted study programs to explore the possible advantages of new technologies before committing them to engine applications.

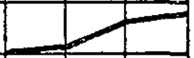
To help alleviate the lengthy process of certification, engine manufacturers have developed real-time data analysis techniques to reduce the tedium of test data reduction, and to accelerate the analysis phase of certification.

Operational barriers to technology have two major sources; the user's past experience with the introduction of new technology, and the exposure to large financial risk based on recent product liability cases. The introduction of the wide-body jets and their new high-bypass-ratio turbofan engines created excessive maintenance burdens and schedule delays for the airlines. New interpretations of product liability laws have caused engine manufacturers to become very cautious about the introduction of new technology into civil transport engines. The manufacturers are aware of these problems. They have established orderly procedures during the engine certification stage to identify and minimize potential first-time usage problems during the introduction of new products. They also offer information dissemination programs to educate the users on new technologies and provide technology support programs on a world-wide basis.

Decision Influencers in Jet Engine Development

In addition to the barriers to innovation in jet engine development that are discussed above, the analysis methodology yields a rank ordering of the importance of decision influencers at each stage of the engine development process. These decision influencers and their rank order are presented in Table 6. The first four columns at the right side of the table indicate the rank order of importance of the decision influencer in each stage. The fifth column presents these data as trend lines to indicate how the ranking changes as the program evolves.

TABLE 6. RANK ORDER OF IMPORTANCE OF DECISION INFLUENCERS IN COMMERCIAL JET ENGINE DEVELOPMENT ACROSS ALL DESIGN AND DEVELOPMENT STAGES

Rank Order (All Design and Development Stages)	Decision Influencer	Rank in Design and Development Stages				
		Preliminary Design	Exploratory Development	Advanced Development	Engineering Development	Trend in Rank Order Over Design and Development Stages (Each Row Independently Scaled)
1	Chief, Engineering*	8	1	1	1	
2	Airlines	1	5	2	2	
3	Airframe Manufacturers	2	5	2	3	
4	Executive Officer*	3	5	5	4	
5	Manager, Preliminary Design and Development*	10	2	2	6	
6	Board of Directors*	6	5	10	6	
6	Finance Director*	6	5	10	6	
8	Marketing Director*	4	11	10	6	
9	Project Director*	11	10	6	5	
10	Strategic Planning Director*	4	11	14	11	
11	Legal Director*	9	11	13	11	
11	Department of Defense	13	2	7	11	
11	NASA	13	2	7	11	
14	FAA/EPA	12	11	7	10	
15	Department of Commerce	13	11	14	11	
15	Department of State	13	11	14	11	
15	Manager, Manufacturing Services*	13	11	14	11	

*Jet Engine Manufacturer

The airlines exert a strong influence throughout the design and development stages. Their influence diminishes somewhat only in the exploratory development stage, where the component technology to meet the airline's requirements is developed.

The airframe manufacturer rates high as an influencer of the engine manufacturer because in a sense, he is a customer of the engine manufacturer. The engine manufacturer must size his engine to meet the projected requirements of the airframe manufacturer.

After concepts are developed based on inputs from the airlines, the airframe manufacturers, the Marketing Director and the Strategic Planner, the Chief of Engineering assumes control of the project and exerts the strongest influence on the introduction of technology and on the whole development process for a new engine.

The Executive Officer of the engine manufacturers exerts his influence early in the development stages and maintains his awareness and influence throughout the program. Here the dominant personality comes into play. It will be seen in the next section that this is in marked contrast to the decision-making process in the airframe industry. It probably is best attributed to the style of doing business in the engine area. While the "dominant personality" leaders have largely left the airframe companies, they still exist in the aircraft engine companies. Also, the Finance Director and Board of Directors have a much stronger role in engine development than their counterparts in the airframe industry.

As indicated in Table 6, the Manager of Preliminary Design and Development is heavily influenced by the inputs from the previously discussed personnel during the preliminary design stage of a new component or engine. However, once he and his design team develop new concepts, he strongly influences the next two stages of the project where the component technology and engine technology are validated.

The Marketing Director exerts his strongest influence during Preliminary Design and as the engine is being considered for production.

The Strategic Planner, who does not have an identifiable counterpart in the airframe manufacturers, exerts his influence in Preliminary

Design and then bows out of the picture because he is responsible for long-term (15 to 20 years) forecasting of the market place and the preparation of long-term company plans for product development.

The influence of the Project Director in the engine manufacturer's organization is similar to that of the airframe manufacturer except that his ranking within the development process is not as high (moderate as opposed to strong) within the respective organizations.

The Legal Director makes his presence known by evaluating the risks and liabilities associated with introducing new technology; however, he apparently does not play a major role in influencing the decisions during engine development.

The Department of Defense and NASA play an unusually strong role in the Exploratory Development stage of jet engines. Historically, the military has funded the development of engine technology that eventually was introduced into civil transport engines. Now, the manufacturers increasingly look to NASA for funding to support these developments because engines being developed for military requirements have diverged from the requirements of civil transports.

The FAA and EPA exert their influence in the Advanced Development stage because there the new and old technology components are integrated and operated as a propulsion unit. At this point in time, the manufacturer demonstrates that he can meet the safety, noise, and pollution regulations imposed on his engine by these agencies.

The Department of Commerce and Department of State have little influence on the technology development for jet engines. However, they do exert an indirect influence on the production decisions because today's engine market is international in scope and the manufacturer must be responsive to Government policies.

Influences in Airframe Development

Tables 3 and 4 indicate that the major barriers to innovation in the airframe industry are somewhat different from those factors that concern the jet engine manufacturers. The three highest ranked barriers shown in Table 3 indicate that the foremost concern of the airframe manufacturers are the long service life and extreme reliability that they must guarantee to the airlines. The current fleet of commercial jet transport aircraft has set a precedent in the transportation industry with regard to both airframe life and engine reliability. The technologies involved are proven, maintenance skills and procedures are established, and the support services and warranties provided by the manufacturers are unparalleled by any other transportation equipment vendor. These conditions must be matched or exceeded by any airframe or engine vendor who wishes to introduce new technology, and it must be done in a way that convinces the airlines of its financial advantages while incurring little or no risk to the airlines. The latter consideration is of particular importance in these days of marginal airline profitability. Unexpectedly high operating or maintenance costs associated with a new aircraft can seriously jeopardize an airline's existence. Also, with large passenger capacities and high court liability judgments, a catastrophic accident can literally bankrupt an airline.

The next 11 barriers, which rank 4 through 13 in Table 3, may be interpreted as a major concern by airframe manufacturers for the very high nonrecurring costs associated with introducing new technology in an airframe. Because of the small production run for airframes relative to engines (several hundred as opposed to several thousand), the nonrecurring costs are of significantly more concern to the airframe manufacturers than to the engine manufacturers. This, combined with market uncertainties, and a conservative attitude on the part of the airlines with regard to accepting new technology, tends to result in an evolutionary acceptance of new technology in airframe design.

The remaining 12 barriers shown on Table 3 are mixed, but several of them, along with a number of the higher ranked barriers shown in Table 4, are related to recurring costs; both in production and maintenance of the airframes. Uncertainties associated with the cost of manufacture using new technologies such as composite secondary and primary structure, as well as the cost to the airlines of maintaining such structures, may lead to conservative decisions regarding the introduction of this new airframe technology.

As was the case for the commercial jet engine manufacturers, the airframe manufacturers have instituted steps to help overcome many of the barriers listed in Tables 3 and 4. These actions are briefly discussed in Table 7.

Operations related barriers, such as questions of liability, investment enthusiasm, and aircraft maintenance, which rank relatively high in the listing, are all addressed to the extent possible in the manufacturers' programs. By supporting engineering developments of new technologies, they attempt to reduce the risk associated with introduction of new technology into future commercial aircraft. However, it is not possible to substantially reduce two of the major barriers (i.e., "Liability Considerations" and "Lack of Investment Enthusiasm in a Maturing Industry") without major demonstrations of satisfactory use of the new technology and an improved economic picture for the airlines.

The airframe manufacturers continue to seek new ideas for improved airframe fabrication to maintain their superior international position. In contrast to the engine manufacturers, barriers caused by personal bias and tradition rank relatively low, probably because the airframe pioneers who were the powerful leaders in the growing aviation industry have died or retired, and the new leaders have taken proactive steps to overcome personal biases (e.g., creating teams of R&D, design, and production personnel to solve problems and using matrix management for projects).

The manufacturers are now evolving a broad-based working knowledge of composite structures for civil transport applications. They have used composites extensively in non-flight-critical components of the aircraft with good success. Company teams of scientists, designers, and production specialists have been formed to accelerate the acceptance of new technology for production. Programs are implemented to enhance the acceptance of advance composite structure by demonstrating the lower cost fabrication methods.

However, in the area of long-lifetime design, the manufacturers are almost at cross purposes. They now are developing techniques to more than double the lifetimes of current transport airframes using conventional

TABLE 7. KEY BARRIERS TO INNOVATION AND INTERACTIONS WITH MANUFACTURERS' PROGRAMS

(COMMERCIAL AIRFRAME DEVELOPMENT)

Rank Order	Barriers to Innovation	Interactions With Manufacturers' Programs
1a	Long lifetime design requirement for commercial air transports.	Airframe manufacturers need to establish strong R&T programs to demonstrate to airlines that new airframe technologies can provide significant long-lived performance improvement over conventional technologies at lower costs. This will be a difficult task now that airlines believe that they can increase the service life of current aircraft up to 80,000 hours and operate them economically.
1b	Service-time required to develop confidence for designer and customer acceptance of new technology.	Manufacturers have in-house programs to develop new airframe technologies and to obtain in-flight service experience on non-flight-critical components. However, more extensive demonstrations, are needed to develop customer acceptance of new technology involving flight-critical components.
3	Liability considerations	New interpretations of product liability laws have caused the manufacturers to become very cautious about the introduction of new technology into civil transports because of the financial risk and the airline's reluctance to buy aircraft that depart from proven technologies.
4a	Certifying the use of new technology by FAA for commercial aircraft	Airframe manufacturers must continually keep FAA aware of the latest advances in new technology applications and their experience with demonstration programs to avoid extended delays in receiving FAA approvals for its use.
4b	Cost of demonstration programs	Airframe manufacturers must continue to find ways to reduce the cost of new technology demonstration programs.
6	Company traditions/personalities	The stability of U.S. civil transport airframe companies relative to foreign manufacturers accompanied by excellent products and good management practice has made them the world leaders. The managers must continue to evaluate new technologies against proven technologies on an objective technical and economic basis.
7	Excessive qualification testing and proof testing	Manufacturers are developing analytical methods based on experimental data which can be used to accelerate test procedures and reduce costs.
8	Lack of investment enthusiasm in a maturing industry (cash flow situation)	The lack of investment in the aircraft industry is caused by the current financial position of the airlines. Potentially, the development and introduction of energy-efficient transports could have long-term economic benefits.
9	Market uncertainty for type and quantity of new aircraft	The marketing staffs of manufacturers have developed sophisticated demand forecasting techniques to minimize the risk of committing to a new or derivative aircraft production run.

TABLE 7. (Continued)

Rank Order	Barriers to Innovation	Interaction With Manufacturers' Programs
10a	Lack of competition from other manufacturers in the use of new technology	The competition to correctly time the introduction of a new design is the critical competitive factor. Because all manufacturers are basically familiar with technical innovations, only a limited amount of unique technology is likely to be introduced in any particular new aircraft.
10b	Historic design practices are favored	Manufacturers break away from historic design practices when they have gained a working familiarity with the new technology and can objectively evaluate it vis-a-vis historic practices.
12	Lack of demonstrated hardware reliability	The manufacturers must demonstrate that new technologies, such as active control systems, as reliable as current technology.
13a	Time at which technology is considered "available" is vastly different for scientists, aircraft designers, and production specialists.	Manufacturers have formed teams consisting of scientists, designers, and production specialists to accelerate the acceptance of a new technology for production
13b	Developing confidence of suppliers and customers that new technologies are sufficiently advanced to justify the use of new material or processes.	For example, airframe manufacturers must convince suppliers that there is a sufficient market for advance composite materials at competitive prices. Further, they must convince airlines that the advance composites will not become a maintenance and operations burden with attendant increased costs.
15	Cost of new technology installed in aircraft	The manufacturer must demonstrate to the airlines that new technologies will result in lower costs on a life-cycle cost basis than would current technology.
16	Due to the need for back-up technologies, it is difficult to exploit new technology to enable radically different vehicle configurations to be developed to reduce life-cycle costs.	New technologies are introduced in a development program on a substitution basis because back-up technologies based on current state of the art must be available to avoid delays in the program. Full advantage of a new technology cannot result until a sufficient experience base exists to take advantage of the unique design possibilities inherent in the technology.
17	Lack of accumulated experience base with new technology	Manufacturers solicit supportive funds to gain experience with new technologies and, in addition, utilize corporate funds to support technology development.
18	Repair or replacement of composite structures after accident (e.g., fire).	Manufacturers must demonstrate to the airlines that advance composite materials are simple and inexpensive to repair. The deterioration of mechanical properties of composites when exposed to high heat remains a barrier to their utilization in structural components.

TABLE 7. (Continued)

Rank Order	Barriers to Innovation	Interaction With Manufacturers' Programs
19a	Rapid rate at which technology is changing	The rapid evolution of technology always provides a seemingly attractive development on the horizon of practicality. Consequently, manufacturers tend to be unwilling to commit to an improved, but interim, technology when they have older technology available and a more attractive alternative on the horizon.
19b	Lack of experience in production adds to uncertainty and risk.	The adaptation of existing fabrication facilities to new technology and the development of experimental production lines are two methods by which manufacturers develop production knowledge and experience.
21	Lack of low-cost methods for composite structure fabrication and nondestructive testing.	Manufacturers have teams of scientists, designers, production and maintenance specialists who are developing low-cost, competitive methods for fabrication and NDT of advance composite structures.
22	Personal biases	Manufacturers need to explore new technology options early in the design and development program so that the options may be evaluated before the costs become prohibitive.
23	Personalities of decision-makers and willingness to take risks	Manufacturers need to explore new technology options early in the design and development program so that the options may be evaluated before the costs become prohibitive.
24	Lack of in-service demonstration as opposed to prediction of performance.	Civil transport manufacturers have cooperative efforts with airlines to demonstrate new technologies to obtain in-service experience quickly. Airlines use their aircraft more intensively than any other operator. However, experimental programs must not jeopardize flight or maintenance schedules or increase the airline's exposure to risk.
25	Lack of identifiable product champion	The airframe manufacturers recognize the role of the product champion and attempt to objectively evaluate his ideas.
26	Development of system design requirements	Manufacturers need to work with the airlines and regulatory agencies to develop realistic system requirements for new technologies, such as active control technology.

structural materials, while trying to accumulate in-flight service experience to demonstrate the usefulness of advanced composite structures. These efforts to extend the lifetimes of current airframes will tend to delay introduction of composite technology.

Finally, because the burden of certification is on the manufacturer, new analytical methods are being investigated which may result in the reduction of tests required to certify the aircraft. These methods would reduce the costs and the time required for certification.

Decision Influencers in Commercial Airframe Development

The decision influencers in the airframe industry and their relative order of importance are listed in Table 8. As was the case with the corresponding table for the engine manufacturers (Table 6), the first four columns at the right indicate the rank order of importance of the decision influencer at each stage of development. The fifth column presents these data as trend line to indicate how their influence changes as development proceeds.

The airlines rank first overall because they are the ultimate buyers of the new aircraft. The manufacturer directs all of his efforts toward developing an aircraft that meets the airlines' requirements and appeals to their preferences.

The Chief of Advanced Design has a strong influence during the Conceptual and Preliminary Design Stages when options for new technology are being evaluated. After the preliminary design is completed, his influence wanes because the design is transferred to the Project Director. During the Conceptual Design Stage, the Marketing Director and Engineering Director exert a strong influence on the design. However, in the next two stages, their influences diverge. The Engineering Director exerts an increasing influence in the process because critical engineering decisions are being made, while the Marketing Director's influence declines, only to be restored when the decision of whether to enter into production is reached.

TABLE 8. RANK ORDER OF IMPORTANCE OF DECISION INFLUENCERS IN COMMERCIAL AIRFRAME DEVELOPMENT ACROSS ALL DESIGN AND DEVELOPMENT STAGES

Rank Order (All Design and Development Stages)	Decision Influencer	Rank in Design and Development Stages				Trend in Rank Order Over Design and Development Stages (Each Row Independently Scaled)
		Conceptual Design	Preliminary Design	Detailed Design	Production	
1	Airlines	1	3	1	1	
2	Engineering Director*	3	1	1	4	
3	Chief, Advanced Design*	2	2	5	7	
4	Engine Manufacturers	5	5	1	1	
5	Project Director*	7	6	1	1	
6	FAA/EPA	6	3	6	10	
7	Marketing Director*	3	8	10	4	
8	NASA	8	7	9	12	
9	Production Director*	9	9	6	7	
9	Chief, Manufacturing Development*	9	9	6	7	
11	Executive Officer*	11	11	10	6	
12	Legal Director	12	12	12	14	
13	Finance Director*	14	14	14	12	
14	Board of Directors*	14	14	14	12	
15	Department of Commerce	15	15	15	14	
16	Department of State	16	16	16	16	
16	Department of Defense	16	16	16	16	

*Airframe Manufacturer

The most powerful outside agents influencing the airframe manufacturers decision are the engine manufacturers. They rank just below the airlines and key influencers within the airframe companies during Conceptual and Preliminary Design and then move up to the first rank with the Project Director and airlines in the Detail Design Stage and Production Stage.

Next, the Government regulatory agencies and research and development agencies exert their influence on the design. The regulations promulgated by the FAA with regard to safety, and by EPA with regard to noise and pollution, require the manufacturers to thoroughly consider these constraints during Preliminary Design. Also, NASA's strongest influence occurs in this stage because at this time, the manufacturers are evaluating technologies often made available through NASA-funded research.

The Production Director and Chief of Manufacturing Development exert a moderate influence during Conceptual and Preliminary Design which increases as the project moves toward production.

The Executive Officer's influence also increases as the project approaches the production stage. His decision is based on a multiplicity of factors, including: (1) the reports of the airlines' reaction to the company design, (2) the engine manufacturers' promises, and (3) his staff's technical and marketing evaluations.

It is shown that the Legal Director, Finance Director and Board of Directors, along with the Departments of State, Commerce, and Defense have only a little influence on the decision to incorporate new technology in a commercial transport. This is not to imply that they have no influence, it only suggests that, historically, technical and marketing influences outrank these six.

FUTURE DEVELOPMENTS IN CIVIL TRANSPORTS

Forecasts of airline activity in the next two decades indicate that there is a market for over $46 billion worth of new transport aircraft. Approximately $19 billion is projected for the replacement of current aircraft. The remainder is required to meet the anticipated worldwide growth of passenger volume during that time frame.(14) The aircraft industry is preparing proposals to respond to the airlines' requirements in the short-term (next 5 years), mid-term (5-10 years), and long-term (beyond 10 years). This section contains a discussion of some of the anticipated engine and airframe developments for future civil transports, and a description of current NASA research in this area.

Future Engine Requirements

Future engine requirements can be classified into short-term, mid-term, and long-term needs. Short-term requirements involve modifications to present in-service engines to improve their competitive position by reducing unscheduled removals, by maintaining performance, etc. Mid-term engine improvements will apply to the new ten-ton engines now undergoing development. Long-term advancements would be applicable to the next generation of engines (beyond the ten-ton engines) which could be available around 1990.

In the short term, a key to implementing technological advances is competitive pressure. This is especially true in the current high-bypass-ratio turbofan competition. To maintain CF6 performance guarantees, GE is investigating two causes of engine efficiency degradation: dirty compressors and turbine-blade rubbing.(15) However, GE's main short-term attention has been on solving bird ingestion problems. P&WA has also experienced blade rubbing problems on the JT9D, but within the compressor and not the turbine. An expensive refurbishment program is now underway which involves replacement of the blade tip rubbing strips, reprofiling and replacing some blades.

P&WA's JT8D has been in the enviable position of having essentially no competition. As a result, P&WA has been reluctant to invest its own funds in technology improvement programs for these engines. However, a program has been launched recently to develop a new family of JT8D engines, designated the -200 series. These engines capitalize on the technology developed in the NASA JT8D Refan Program to provide significant reductions in aircraft noise, while also offering increased thrust and reduced specific fuel consumption.

The new aircraft engines for the 1980s will be the CFM56 and JT10D ten-ton engines. Scheduled for certification within the next few years, these engines have been designed for fuel efficiency, airline economics, and environmental compatibility. The incorporation of advanced design philosophy and technological features results in a cruise fuel consumption improvement of 20 percent relative to present turbofans in the same thrust class. Improvements in aerodynamic and structural technology have permitted the use of fan blades with lower aspect ratio and wider chords. Inexpensive fiberglass - epoxy composite materials are being used in low temperature non-structural applications (e.g., fan exhaust struts). Turbines are making use of better materials and improved cooling systems.

In the long term, the engine companies are also concentrating their efforts on reducing fuel consumption, engine price, and maintenance costs. Engine companies are especially sensitive to maintenance problems because of loss of the "good will" with the airlines as a result of schedule delay, lost seats, etc. Improvements in these areas must be balanced against environmental acceptability. Starting at the front of the engine, 3-4 percent improvements in fan efficiency are expected in the next generation engines. This will result mainly from advanced technology fan blades which will have wider chords, improved airfoil shape, and a single damper shroud. Compressor efficiency is also expected to increase by several percent through better choice of design point and operating line. Perhaps the surest way to reduce cost is to improve turbine durability. New materials providing higher strength at temperature and permitting advanced film cooling techniques are needed. Possibly the single most important dimension in a high temperature turbine affecting its performance is the clearance between the blade and the turbine case seal. By using a ceramic seal surface to reduce seal cooling air requirements, a 1-1/2 percent reduction in specific fuel consumption may be possible. Another major component which impacts costs is the fuel control. With the number of control functions now required, the more precise fuel scheduling provided by a digital computer will reduce fuel consumption. By measuring and limiting turbine metal temperature directly, parts replacement and maintenance costs will be reduced. By combining all of these component improvements with a bypass ratio of 8 to 12 and an overall pressure ratio of 40-50, potential fuel consumption improvement of up to 20 percent may be achieved. However, practical limitations exist. Higher pressure ratios require more costly materials and higher turbine temperatures; the leakage and clearance problems may prove unsolvable.

Future Airframe Technology Requirements

The aircraft industry has divided the projected near- to mid-term market for future aircraft into three broad categories: (1) 100/120 passenger short-range aircraft; (2) a 140/160 passenger short- to mid-range aircraft; and (3) a 200/220 passenger mid- to long-range aircraft. For the long-term, they anticipate a replacement for the current wide-body (250/400 seat) aircraft by the early 1990's.

Several aircraft have been proposed to meet the near- to mid-term requirements. McDonnell-Douglas has proposed a derivative of its DC-9(16), while Fokker has proposed an extensively modified version of its F-28 series aircraft to meet the need for a 100/120 passenger aircraft(17,18). For the 140/160 passenger aircraft, Boeing has proposed the 7N7, the Daussalt-McDonnell combine has proposed the Mercure 200, and British Aircraft proposed a derivative of the BAC-111.(19)

For the 200 passenger aircraft, the aircraft which has created the most interest for near- to mid-term development, there are several proposed aircraft including the Boeing 7X7(20), the Douglas DC-X-200(21,22), and the Airbus 300-B10(19).

In responding to the near-term, the manufacturers are offering essentially existing aircraft with engines modified to meet FAR36 noise standards and to improve fuel consumption slightly.

For the mid-term, the serious contenders have been developing the following technologies to provide a 15 to 20 percent improvement in fuel efficiency. This list includes, in addition to high-bypass ratio engines with improved fuel consumption and reduced noise:(14,17,22)

- Supercritical wing technology
  - thicker wings
  - higher aspect ratios
  - less sweep back
- High-lift devices
  - leading edge and trailing edge flaps
- Improved conventional structural materials and assembly methods
- Composite materials (graphite reinforced) for secondary structure and easily replaceable items such as elevators, rudders, ailerons, fairings, doors, airbrakes, leading and trailing edges and tips of wings.*
- Digital electronics for navigation and all-weather landing, and reduced cockpit complexity.

For the long-term (post 1985), it may be possible to achieve a 40 percent improvement in fuel efficiency.(14) The aircraft industry is studying technologies such as:

- Improved wing aerodynamic design processes, including wing-body blending and wing-engine integration.
- Laminar flow control to reduce drag
- Improved air traffic control such as 4-D navigation control, that is, positive control of time of arrival as well as altitude, spacing, and airspeed.
- Advance metallic and composite structures, including composite primary structures such as the wing torque box and fuselage components.
- Active controls to enhance airplane efficiency through augmentation and control systems.

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* Some of the technical considerations for introducing advanced composites into civil transport airframes are discussed in Appendix B.

NASA's Aircraft Energy Efficiency Program

Propulsion System Technology

Within the NASA Aircraft Energy Efficiency Program, there are two major programs dealing with Propulsion System Technology. The Engine Component Improvement Program is directed at near-term improvements that can be incorporated into current engines to reduce fuel consumption. The Energy Efficient Engine Program is a longer-range effort to demonstrate technology for the next generation, more fuel-efficient, turbofan engine.

The Engine Component Improvement Program has two basic parts: Engine Diagnostics and Performance Improvement. The purpose of the Engine Diagnostics activity is to develop methods to reduce the deterioration in performance that occurs over the life of an engine. The Performance Improvement portion of this program is aimed at developing components which would reduce the fuel consumption of current U. S. commercial engines and be ready for introduction into new production versions of these engines in the 1980 - 1982 time period.(23)

Current NASA plans are directed at improved turbine cooling, blading seals and clearance control, exhaust nozzle mixers and digital electronic controls. These improvements are anticipated to be available for JT8D's, JT9D's, and CF6's in the 1980 - 1982 time period. The project schedule has been constructed so as to be compatible with standard engine development procedures.

The Energy Efficient Engine program will provide the technology base for significant reductions in fuel consumption for all new turbofan engines. Engine requirements will include a more efficient cycle, improved aerodynamic performance, better seals, reduced clearances, and higher-temperature materials. Current technology cannot provide these fuel-saving improvements and technology advances must be pursued in every component of the engine.(24) The NASA Task Force recommended $175 million for the Energy Efficient Engine program over an eleven year period, in a schedule that appears to be consistent with a 1990 date of entry.

Airframe Technology

The NASA Aircraft Energy Efficiency (ACEE) program has two programs aimed at improvements in aircraft configurations. In the Energy Efficient Transport program, efforts are placed on the development of advanced aerodynamics and active controls for near-term application to derivative or new transports. Areas being studied are: high aspect ratio wings incorporating supercritical airfoil sections, winglets, advanced high-lift devices, integrated airframe-propulsion systems, and active controls. The second aerodynamic program is Laminar Flow Control (LFC). It is aimed at achieving low-drag laminar flow control systems for transport aircraft. This program includes engineering investigations, analyses, design studies, and component tests necessary to evaluate alternative LFC design concepts.(23)

The remaining element of the ACEE program is the Composites Primary Aircraft Structures program. The objective of this program is to provide the technology for reducing air transport fuel consumption by the use of composite materials to reduce the weight of new aircraft. The program includes the design, development, certification and flight service of secondary structures, moderate size primary structures, and a wing. The program is designed to permit increasing experience with these new materials and processes leading to the development of large primary structures.(23)

The NASA Task Force recommended additional funding of $50 million over 6 years for the Energy Efficient Transport program; $100 million for the Laminar Flow Control program over the next 10 years; and $110 million during the next 6 years for the Composites Primary Structures program. These programs should provide an improved technology base for aircraft being developed for the 1990's.

CONCLUSIONS

In this study, the process by which both jet and airframe manufacturers decide to invest in new technology has been examined. An analysis methodology was developed and applied to identify the rank ordering of importance of barriers to innovation in both the engine and airframe industries as well as the importance of various decision influencers at each stage of development. Comparison of the barriers in the two industries leads to the conclusions that:

(1) Decisions to introduce new technology in jet engine development are heavily influenced by considerations

  (a) Life-cycle cost competitiveness of the design
  (b) Past experience with new technology and a generally conservative attitude toward product development
  (c) Uncertainties in development time caused by new technology.

(2) Due to the larger production runs of engines versus airframes, nonrecurring development costs can be more easily amortized in engine production and are consequently of less concern. This fact may, in part, motivate the long and thorough development process that engine manufacturers undertake to ensure a satisfactory end product.

(3) The airframe manufacturers design and development decisions are heavily influenced by

  (a) The need to meet performance and service guarantees
  (b) The need to control nonrecurring costs in the airframe development process because of their limited ability to amortize these costs across large production runs.
  (c) The possibility of recurring costs associated with uncertainties about manufacturing and maintenance costs.

In both the jet engine and airframe industries, remarkable actions have been taken and programs have been instituted to prevent these barriers to innovation from bringing technical stagnation to the industry. It is to their managers' credit that they have been willing to literally risk their future on billion-dollar aircraft and engine developments, while at the same time advancing the technical state of the art through the introduction of new technology.

This type of business management performance results from a complex set of interactions among decision influencers in the two industries. The complementary interactions of airframe and engine manufacturers with each other and with the airlines has enabled the commercial air industry as a whole to produce and operate increasingly productive aircraft.

There are significant differences in the way that decisions are made in the development of engines and airframes. The engine manufacturers tend to be influenced more by dominant personalities than do the airframe manufacturers, but are also more dependent on long-range planning due to the exceptionally long engine development process. The airframe manufacturers, with their short development cycle, must respond to the airline market and when that market results in the definition of a new aircraft, depend heavily on the design and development decisions of their technical managers.

When planning Government support of technical development, it is significant to note that NASA and FAA/EPA have a strong and continuing influence in all three design stages leading to airframe production. In contrast to this, during jet engine development, DOD and NASA are the second most important decision influencers in the Exploratory Development Stage. They must essentially "hit" this window in the development cycle with their technical contributions because their influence drops off sharply after this stage.

The next generation of civil transport aircraft and engines may well be developed under international consortium agreements. Under such arrangements, Pratt & Whitney Aircraft and General Electric, the two foremost aircraft engine companies in the world, will want to maintain primary control over the engine development by being responsible for the engine core. Therefore, for NASA to be most responsive to U.S. needs, they should concentrate long-term research efforts on core-related technologies. In the realm of airframe technology, the U.S. has a superior position in the management and application of manufacturing technology. This talent coupled with supportive programs to develop advanced aerodynamic concepts, active control systems, and new materials for aircraft structures, will allow the U.S. to maintain that position.

Individuals with a variety of technical, financial, and legal backgrounds participate in a complex set of interactions to reach design and development decisions for new civil transport aircraft. In this report, the technical barriers to the introduction of new technology have been defined and a technique developed and applied for evaluating their relative importance at each stage in the aircraft development process. A decision framework and the parties involved in the decision processes required for the introduction of new technology have been identified and examined to determine both their relative overall influence and how that influence enters into decisions at each stage of the aircraft and engine development processes. In any particular development program, the detailed interactions among groups and individuals in the manufacturers' organizations, as well as with the airlines and regulatory agencies, occurs in a complex and unique manner as dictated by the needs of the program. This report provides an improved understanding of the barriers to innovation and of the roles that key individuals play in determining the technology for new aircraft. It is a first step toward understanding the decision-making process by which new technology is incorporated in civil air transport.

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APPENDIX A

STRUCTURED DATA AND ANALYSES

APPENDIX A

STRUCTURED DATA AND ANALYSES

Subsequent to interviews with the two major U.S. commercial jet engine and three commercial airframe manufacturers, the interviewers were asked to fill out the sets of matrices shown in Figures A-1 and A-2. They were requested to fill in only important interactions. The relative sparsity of the engine matrix compared to the airframe matrix primarily reflects a difference in the threshold levels of what is or is not considered to be important by the two independent groups of interviewers. This, however, does not affect the results of the analysis since engines and airframes are analyzed independently. A "1" entered in a cell of the matrix indicates that an important interaction occurs between the two factors that intersect to form that cell. Similarly, an "0" indicates that a less critical or no interaction occurs.

As mentioned in the main body of the report, the interviewers were asked to produce composite views of the three airframe and two engine manufacturers when filling out the respective airframe and engine matrices. Thus, Figure A-1 represents their perception of the important interactions affecting the introduction of new technology in commercial jet engines by Pratt & Whitney and General Electric. Similarly, Figure A-2 represents the Boeing, Lockheed and Douglas composite view of the interactions among factors involved with the introduction of new technology in commercial airframes.

This method of documentation has certain drawbacks--not the least of which is the fatigue that sets in after several hours of filling out matrices--but it does force the interviewers to rigorously consider and make a judgment about each interaction in the complex decision process involved in the design and development of new engines and airframes. It also facilitates recording the interactions that the interviewers are most confident of and, through subsequent analyses, deriving the other interactions.

Figures A-1 and A-2 were designed to allow the interviewers to document interactions between Barriers to Innovation and Decision Influencers, between Decision Influencers and Design Criteria, and between Design Criteria and Design and Development Stages. Appropriate matrix multiplication resulted in the matrices shown in Figures A-3 through A-6, which indicate the interactions between

- Decision Influencers and Commercial Jet Engine Design and Development Stages
- Decision Influencers and Commercial Air Transport Design and Development Stages
- Barriers to Innovation and Commercial Jet Engine Design and Development Stages
- Barriers to Innovation and Commercial Air Transport Design and Development Stages,

respectively.

The matrix entries reflect the relative levels of interaction and can be summed to rank order:

(1) The relative importance of Decision Influencers within each Design Stage.

(2) The relative importance of Barriers to Innovation within each Design Stage.

These scores and corresponding rank orders are shown in the columns adjacent to the matrices. Also shown are the scores summed across all Design and Development Stages and the overall rank order of the Decision Influencers and Barriers to Innovation.

A word of caution is in order regarding the interpretation of results obtained through this type of analysis. Because the results are quantified and highly structured, there is a tendency to assign more credibility to the specific rankings than is warranted.

Due to the somewhat subjective basis for the rank orders, the precision is not great and a difference of item places in rank order should not be considered significant. Major differences in rank order (i.e., more than 5 to 10 positions in rank) are probably significant. It is on this order of comparison that the results will be evaluated and conclusions drawn.

It is also noted that, while the rank ordering is generated with the most significant Barriers to Innovation given the highest rank (lowest cardinal number), a view from the other end of the barriers list provides considerable insight into the manufacturer's decision-making process. Many factors that are often considered to be barriers to innovation in other industries have apparently been overcome by the commercial airframe and jet engine manufacturers.

FOLDOUT FRAME 1

General Technology Considerations (Barriers to Innovation)

1 Due to the need for backup technologies, it is difficult to exploit new technology to enable radically different vehicle configurations to be developed to reduce life cycle cost
2 Relatively small performance savings associated with any particular component combined with the need to take incremental steps in innovative design
3 Rapid rate at which technology is changing
4 Time to implement technology on a production basis
5 Long lifetime design requirement for commercial aircraft
6 Time required to certify new technology
7 Certifying the use of new technology by FAA for commercial aircraft
8 Lack of low cost methods for composite structure fabrication and nondestructive testing
9 Service time required to develop confidence for designer and customer acceptance of new technology

	Decision Influencers	1	2	3	4	5	6	7	8	9
Engine Manufacturers	Board of Directors	0	0	0	0	0	0	0	0	0
	Executive Officer	0	0	0	0	0	0	0	0	0
	Legal Director	0	0	0	0	0	0	0	0	0
	Finance Director	0	0	0	0	0	0	0	0	0
	Marketing Director	0	0	0	0	0	0	0	0	0
	Chief, Engineering	1	1	0	1	1	1	1	1	0
	Manager, Preliminary Design and Development	1	1	0	1	1	1	1	0	0
	Project Director	0	0	0	0	1	1	1	1	1
	Strategic Planning Director	0	0	0	0	0	0	0	0	0
	Manager, Engineering Services	0	0	0	0	0	0	0	1	0
	Airlines	0	0	0	1	0	0	0	1	1
	FAA/EPA	0	0	0	1	0	0	0	1	1
	Department of Commerce	0	0	0	0	0	0	0	0	0
	Department of State	0	0	0	0	0	0	0	0	0
	Department of Defense	0	0	0	0	0	0	0	0	0
	NASA	0	0	0	0	1	1	1	1	1
	Airframe Manufacturers	1	0	0	0	0	1	1	0	1

Engine Technology Considerations

10 Material characteristics
11 Turbine cooling
12 Blade manufacturability
13 Foreign object impact resistance
14 Bearing/rotor design
15 Seal design
16 Turbine stage loading
17 Integrated nacelle design
18 Disc containment

	Decision Influencers	10	11	12	13	14	15	16	17	18
Engine Manufacturers	Board of Directors	0	1	0	0	0	0	0	0	0
	Executive Officer	0	1	0	0	0	0	1	0	0
	Legal Director	0	0	0	0	0	0	0	0	0
	Finance Director	0	0	0	0	0	0	0	0	0
	Marketing Director	0	0	0	0	0	0	0	0	0
	Chief, Engineering	1	1	1	1	1	1	1	1	1
	Manager, Preliminary Design and Development	0	0	0	0	1	0	0	1	0
	Project Director	0	0	0	0	0	0	0	0	0
	Strategic Planning Director	0	0	0	0	0	0	0	0	0
	Manager, Engineering Services	1	1	1	0	0	0	0	0	0
	Airlines	0	0	0	1	0	0	0	0	1
	FAA/EPA	0	0	0	1	0	0	0	0	1
	Department of Commerce	0	0	0	0	0	0	0	0	0
	Department of State	0	0	0	0	0	0	0	0	0
	Department of Defense	0	0	0	0	0	0	0	0	0
	NASA	0	0	0	0	0	0	0	0	0
	Airframe Manufacturers	0	0	0	0	0	0	0	1	0

Economic Considerations

19 Lack of investment enthusiasm in a maturing industry (cash flow situation)
20 Cost of demonstration programs
21 Patent/license considerations
22 Nonproprietary nature of results obtained through NASA's program
23 Market uncertainty for type and quantity of new aircraft
24 Financing of new production facilities when visibility is limited on aircraft procurements and rates
25 Disposal or conversion of production facilities for conventional technology
26 Disposal of existing production machinery that may not be fully amortized
27 Cost of new technology installed in aircraft
28 Lack of competition from other manufacturers in the use of new technology
29 The cost of tooling at all stages of manufacturing sequence using new technology
30 Lack of production machinery infrastructure to produce machinery for new technology

	Decision Influencers	19	20	21	22	23	24	25	26	27	28	29	30
Engine Manufacturers	Board of Directors	1	0	0	0	0	1	0	0	0	0	0	0
	Executive Officer	1	0	1	0	1	1	1	0	1	0	0	0
	Legal Director	0	0	1	0	0	0	0	0	0	0	0	0
	Finance Director	0	0	0	0	0	1	1	1	1	0	1	0
	Marketing Director	1	0	0	0	0	0	0	0	1	1	0	0
	Chief, Engineering	0	0	0	0	0	0	0	0	1	1	0	1
	Manager, Preliminary Design and Development	0	0	0	0	0	0	0	0	0	0	0	0
	Project Director	0	1	0	0	0	0	1	0	1	0	1	1
	Strategic Planning Director	1	0	1	0	1	0	0	0	0	0	0	0
	Manager, Engineering Services	0	0	0	0	0	1	1	1	0	1	1	1
	Airlines	1	1	0	0	0	0	0	0	1	1	0	0
	FAA/EPA	0	0	0	0	0	0	0	0	0	0	0	0
	Department of Commerce	0	0	1	0	0	0	0	0	0	0	0	0
	Department of State	0	0	1	0	0	0	0	0	0	0	0	0
	Department of Defense	0	0	1	0	0	0	0	0	0	0	0	0
	NASA	0	0	0	0	0	0	0	0	0	0	0	0
	Airframe Manufacturers	0	0	0	0	0	0	0	0	1	1	0	0

Social Considerations

31 Adequacy of materials supply infrastructure
32 Airline reluctance to use new technology
33 Public reaction to new technology
34 Lack of trained maintenance personnel
35 Lack of accumulated experience base with new technology
36 Conservative designs avoiding risk (due to publicity afforded failure) may not exploit the potential advantages of new technology
37 Lack of in-service demonstration as opposed to prediction of performance
38 Liability considerations
39 Lack of recognition of need for advancement
40 Lack of pressure from customers for more economical equipment
41 Difficulty in recruiting adequately trained designers, production personnel, etc. who can work with new technology
42 Union objections to changing technology
43 Lack of training of production workers

	Decision Influencers	31	32	33	34	35	36	37	38	39	40	41	42	43
Engine Manufacturers	Board of Directors	0	0	0	0	0	0	0	0	0	0	0	0	0
	Executive Officer	0	0	0	0	0	1	0	0	0	0	0	1	0
	Legal Director	0	0	0	0	0	1	0	1	0	0	0	1	0
	Finance Director	0	0	0	0	0	0	0	1	0	0	0	0	0
	Marketing Director	0	1	1	0	0	0	0	0	0	0	0	0	0
	Chief, Engineering	0	0	0	1	1	0	0	0	0	0	1	0	0
	Manager, Preliminary Design and Development	0	0	0	0	0	0	0	0	0	0	0	0	0
	Project Director	1	0	0	1	1	0	0	0	0	0	1	0	1
	Strategic Planning Director	0	0	0	0	0	0	0	0	0	0	0	1	0
	Manager, Engineering Services	1	0	0	0	1	0	0	0	0	0	1	1	1
	Airlines	0	1	1	1	1	1	1	1	0	0	0	0	0
	FAA/EPA	0	0	0	0	0	0	0	0	0	0	0	0	0
	Department of Commerce	0	0	0	0	0	0	0	0	0	0	0	0	0
	Department of State	0	0	0	0	0	0	0	0	0	0	0	0	0
	Department of Defense	0	0	0	0	0	0	0	0	0	0	0	0	0
	NASA	0	1	1	0	0	0	0	0	0	0	0	0	0
	Airframe Manufacturers	0	1	1	1	1	1	1	1	0	0	0	0	0

Management Considerations

44 Personal biases
45 Personalities of decisionmakers and willingness to take risk
46 Company traditions/personalities
47 Program management structure — matrix versus hierarchical
48 Historic design practices are favored
49 NIH factors
50 Lack of an identifiable product champion
51 Time at which technology is considered to be "available" is vastly different for scientists, aircraft designers, and production specialists
52 Lack of experience in production adds to uncertainty and risk
53 Developing confidence of suppliers and customers that new technologies are sufficiently advanced to justify the use of new materials or processes
54 Export controls (CoCom list)

	Decision Influencers	44	45	46	47	48	49	50	51	52	53	54
Engine Manufacturers	Board of Directors	0	0	0	0	0	0	0	0	0	0	0
	Executive Officer	1	1	1	1	0	0	1	0	0	0	0
	Legal Director	0	0	0	0	0	0	0	0	0	0	0
	Finance Director	0	0	0	0	0	0	0	0	0	0	0
	Marketing Director	0	0	0	0	0	0	0	1	0	1	0
	Chief, Engineering	1	1	1	1	1	1	0	1	1	0	0
	Manager, Preliminary Design and Development	0	0	0	0	1	0	0	0	0	0	0
	Project Director	0	0	0	1	0	0	0	1	1	0	0
	Strategic Planning Director	0	0	0	0	0	0	0	0	0	1	0
	Manager, Engineering Services	0	0	0	0	0	0	0	0	1	0	0
	Airlines	1	1	1	0	0	0	0	0	0	0	0
	FAA/EPA	0	0	0	0	0	0	0	0	0	0	0
	Department of Commerce	0	0	0	0	0	0	0	0	0	0	1
	Department of State	0	0	0	0	0	0	0	0	0	0	1
	Department of Defense	0	0	0	0	0	0	0	0	0	0	1
	NASA	0	0	0	0	0	0	0	0	0	0	0
	Airframe Manufacturers	1	1	1	0	0	0	0	0	0	0	0

FOLDOUT FRAME 2

	Commercial Jet Engine Design and Development Stages	Market Criteria			Economic Criteria						Engine Design Criteria								
		Payload/Range Requirements	Number of Aircraft Required by Type (Engines per Aircraft)	Timing of Aircraft Need	Engine Development Cost	Engine Unit Cost	Availability of External Funds (IR&D, Direct Contracts . . .)	Aircraft Direct Operating Cost	Airline's ROI	Engine Manufacturer's ROI	Engine Performance (Takeoff & Landing, Cruise . . .)	Environmental Constraints (Noise, Pollution . . .)	Aerothermo Characteristics (Temperature, Pressure, . . .)	Engine Maintainability/Reliability	Engine Design Lifetime (Hours and Cycles)	Auxiliary Power Requirements	Engine Growth Capability	Engine Structural Integrity	Engine Controls
Preliminary Design	Evaluate market forecasts	0	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
	Define engine size and cycle	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1
	Develop conceptual design of engine configuration	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0
	Estimate engine weight	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0
	Estimate engine costs (production)	0	1	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0
	Perform IOC, DOC, and ROI analyses	1	1	1	0	1	0	1	0	1	0	0	0	1	0	0	0	0	0
	Perform tradeoffs	1	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0
	Define derivative engines	1	1	1	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0
Exploratory Development	Select potential technologies	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0
	Develop alternative technologies	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	1	0
	Develop alternative components	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	1	0
	Test and evaluate components	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	1
Advanced Development	Demonstrate alternative technologies/components	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	1	0
	Test alternative components on slave engines	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	1	0
	Perform component integration tests	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	1	1
	Evaluate alternative engine technologies and components	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	1	1
	Develop flight engine configured mockups	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1
Engineering Development	Develop demonstrator engine	0	0	1	1	1	0	0	1	0	0	0	0	1	1	0	1	0	1
	Perform qualification tests and make production decision	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	1	1

	Decision Influencers	Market Criteria			Economic Criteria						Engine Design Criteria								
	Design Criteria	Payload/Range Requirements	Number of Aircraft Required by Type (Engines per Aircraft)	Timing of Aircraft Need	Engine Development Cost	Engine Unit Cost	Availability of External Funds (IR&D, Direct Contracts . . .)	Aircraft Direct Operating Cost	Airline's ROI	Engine Manufacturer's ROI	Engine Performance (Takeoff & Landing, Cruise . . .)	Environmental Constraints (Noise, Pollution . . .)	Aerothermo Characteristics (Temperature, Pressure, . . .)	Engine Maintainability/Reliability	Engine Design Lifetime (Hours and Cycles)	Auxiliary Power Requirements	Engine Growth Capability	Engine Structural Integrity	Engine Controls
Engine Manufacturers	Board of Directors	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0
	Executive Officer	0	0	0	1	1	0	0	1	1	1	0	0	0	0	0	1	0	0
	Legal Director	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Finance Director	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0
	Marketing Director	0	0	0	0	1	0	1	0	1	0	0	0	0	1	0	0	0	0
	Chief, Engineering	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0	1	1	1
	Manager, Preliminary Design and Development	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0
	Project Director	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
	Strategic Planning Director	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Manager, Engineering Services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Airlines	1	1	1	0	0	0	1	0	0	1	0	0	1	1	0	0	0	1
	FAA/EPA	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	Department of Commerce	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Department of State	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Department of Defense	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	NASA	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	Airframe Manufacturers	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	0	0	1

FIGURE A-1. INTERACTIONS BETWEEN BARRIERS TO INNOVATION, DECISION INFLUENCERS, DESIGN CRITERIA, AND COMMERCIAL JET ENGINE DESIGN AND DEVELOPMENT STAGES

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

FOLDOUT FRAME 1

	Barriers to Innovation	General Technology Considerations								Airframe Technology Considerations				
										Composite Materials				
	Decision Influencers	1 Due to the need for backup technologies, it is difficult to exploit new technology to enable radically different vehicle configurations to be developed to reduce life cycle cost	2 Relatively small performance savings associated with any particular component combined with the need to take incremental steps in innovative design	3 Rapid rate at which technology is changing	4 Time to implement technology on a production basis	5 Long lifetime design requirement for commercial aircraft	6 Certifying the use of new technology by FAA for commercial aircraft	7 Lack of low cost methods for composite structure fabrication and nondestructive testing	8 Service time required to develop confidence for designer and customer acceptance of new technology	9 Repair or replacement of composite structures after accident, e.g., fire	10 Cost of establishing property matrix of composite material	11 Interface of composites with metallic structures (e.g., complex, costly joints)	12 Development of advanced design and manufacturing technologies for large airframe structures to reduce number of joints and fasteners, and hence, part count	13 Direct substitution of parts (composite for metal) does not allow opportunity in design to exploit advantageous characteristics of composites
Airframe Manufacturers	Board of Directors	0	0	0	0	0	0	0	0	0	0	0	0	0
	Executive Officer	0	0	0	0	1	1	0	1	1	0	0	0	0
	Legal Director	0	0	0	0	0	1	0	1	0	0	0	0	0
	Finance Director	1	0	0	0	0	1	0	1	1	0	0	0	0
	Marketing Director	0	0	0	0	1	0	0	1	0	0	0	0	0
	Engineering Director	1	0	1	1	1	1	1	1	0	1	1	1	1
	Chief, Advanced Design	0	0	0	0	1	1	1	0	1	1	1	1	1
	Project Director	1	0	1	1	1	1	1	1	1	1	1	1	1
	Production Director	1	1	1	1	0	0	1	1	0	0	1	1	0
	Chief, Manufacturing Development	0	0	0	0	0	0	0	0	0	0	0	0	0
	Airlines	1	0	1	0	1	1	1	1	1	0	0	0	0
	FAA/EPA	1	0	1	0	1	1	1	1	1	0	1	1	0
	Department of Commerce	0	0	0	0	1	1	0	0	0	0	0	0	0
	Department of State	0	0	0	0	0	0	0	0	0	0	0	0	0
	Department of Defense	1	0	0	0	0	0	0	1	1	0	0	0	0
	NASA	0	0	0	0	1	1	0	1	0	0	0	0	0
	Engine Manufacturer	1	0	1	1	1	0	0	1	1	0	0	0	1

	Barriers to Innovation	Airframe Technology Considerations					Economic Considerations							
		Composite Materials		Active Controls										
	Decision Influencers	14 Developing low-cost methods for fabricating high-quality composite structures	15 Excessive qualification testing and proof testing	16 Development of system design requirements	17 Improved preliminary design weight estimate and payoff methods	18 Lack of demonstrated hardware reliability	19 Lack of investment enthusiasm in a maturing industry (cash flow situation)	20 Cost of demonstration programs	21 Patent/license considerations	22 Nonproprietary nature of results obtained through NASA's program	23 Market uncertainty for type and quantity of new aircraft	24 Financing of new production facilities when visibility is limited on aircraft procurements and rates	25 Disposal or conversion of production facilities for conventional technology	26 Disposal of existing production machinery that may not be fully amortized
Airframe Manufacturers	Board of Directors	0	0	0	0	1	1	1	0	0	1	1	0	0
	Executive Officer	0	0	0	0	1	1	1	0	0	1	1	1	1
	Legal Director	0	0	0	0	1	0	0	1	0	0	0	0	0
	Finance Director	0	0	0	0	1	1	1	1	0	1	1	1	1
	Marketing Director	0	0	0	0	0	1	0	0	0	1	0	0	0
	Engineering Director	1	1	1	0	1	1	1	0	0	1	1	1	0
	Chief, Advanced Design	0	1	1	1	1	0	1	0	0	0	0	0	0
	Project Director	0	1	1	1	1	1	1	0	0	1	1	1	0
	Production Director	1	0	0	0	0	1	0	0	0	1	1	1	1
	Chief, Manufacturing Development	0	0	0	0	0	0	0	0	0	0	0	1	0
	Airlines	0	1	1	0	1	1	1	0	0	1	0	0	0
	FAA/EPA	0	1	1	0	1	0	0	0	0	0	0	0	0
	Department of Commerce	0	0	0	0	0	1	1	1	0	0	0	0	0
	Department of State	0	0	0	0	0	0	0	0	0	0	0	0	0
	Department of Defense	1	1	0	0	1	0	1	1	0	0	0	0	0
	NASA	1	1	0	0	0	0	1	1	0	0	0	0	0
	Engine Manufacturer	1	1	0	0	0	1	1	1	0	1	1	1	1

	Barriers to Innovation	Economic Considerations					Social Considerations							
	Decision Influencers	27 Cost of new technology installed in aircraft	28 Lack of competition from other manufacturers in the use of new technology	29 The cost of tooling at all stages of manufacturing sequence using new technology	30 Lack of production machinery infrastructure to produce machinery for new technology	31 Adequacy of materials supply infrastructure	32 Airline reluctance to use new technology	33 Public reaction to new technology	34 Lack of trained maintenance personnel	35 Lack of accumulated experience base with new technology	36 Conservative designs avoiding risk (due to publicity afforded failure) may not exploit the potential advantages of new technology	37 Lack of in-service demonstration as opposed to prediction of performance	38 Liability considerations	39 Lack of recognition of need for advancement
Airframe Manufacturers	Board of Directors	0	0	0	0	0	0	0	0	0	0	1	1	0
	Executive Officer	1	0	0	0	0	0	1	0	0	0	1	1	1
	Legal Director	0	0	0	0	0	0	0	0	0	0	1	1	0
	Finance Director	1	0	0	0	0	0	0	0	0	0	0	1	0
	Marketing Director	1	0	0	0	0	1	0	0	0	0	1	0	0
	Engineering Director	1	1	1	1	1	1	0	1	1	1	0	1	0
	Chief, Advanced Design	0	1	0	0	0	0	0	0	1	1	1	0	0
	Project Director	1	1	1	1	1	1	0	1	1	1	1	1	0
	Production Director	1	1	1	1	1	0	0	0	0	0	0	0	0
	Chief, Manufacturing Development	0	1	0	0	0	0	0	0	0	0	0	0	0
	Airlines	1	1	0	0	0	1	1	1	1	0	1	1	1
	FAA/EPA	0	0	0	0	0	0	0	1	1	0	1	1	0
	Department of Commerce	0	0	0	0	0	0	0	0	0	0	0	0	0
	Department of State	0	0	0	0	0	0	0	0	0	0	0	1	0
	Department of Defense	1	0	0	0	0	0	0	0	1	0	0	1	0
	NASA	1	0	0	0	0	0	0	0	1	0	0	1	0
	Engine Manufacturer	0	1	1	1	1	1	0	0	0	1	0	1	1

	Barriers to Innovation	Social Considerations		Management Considerations										
	Decision Influencers	40 Lack of pressure from customers for more economical equipment	41 Difficulty in recruiting adequately trained designers, production personnel, etc., who can work with new technology	42 Personal biases	43 Personalities of decisionmakers and willingness to take risk	44 Company traditions/personalities	45 Program management structure – matrix versus hierarchical	46 Historic design practices are favored	47 NIH factors	48 Lack of an identifiable product champion	49 Time at which technology is considered to be "available" is vastly different for scientists, aircraft designers, and production specialists	50 Lack of experience in production adds to uncertainty and risk	51 Developing confidence of suppliers and customers that new technologies are sufficiently advanced to justify the use of new materials or processes	52 Export controls (CoCom list)
Airframe Manufacturers	Board of Directors	0	0	0	1	1	0	0	0	0	0	0	0	0
	Executive Officer	0	1	1	0	1	0	1	0	1	1	0	1	0
	Legal Director	0	0	1	1	1	0	1	0	0	0	0	0	0
	Finance Director	0	0	0	1	1	0	0	0	0	0	0	0	0
	Marketing Director	0	0	0	0	1	0	0	0	0	0	0	0	0
	Engineering Director	0	1	1	1	1	0	1	1	1	1	1	1	0
	Chief, Advanced Design	0	0	0	0	0	0	0	1	0	0	0	0	0
	Project Director	0	1	1	1	1	0	1	1	1	1	1	1	0
	Production Director	0	1	1	1	1	0	1	0	1	1	1	1	0
	Chief, Manufacturing Development	0	0	0	0	0	0	0	1	0	0	0	0	0
	Airlines	0	0	1	1	1	0	1	0	1	1	1	1	0
	FAA/EPA	0	1	0	0	0	0	1	0	1	1	1	1	0
	Department of Commerce	0	0	0	0	0	0	0	0	0	0	0	0	1
	Department of State	0	0	0	0	0	0	0	0	0	0	0	0	1
	Department of Defense	0	0	0	0	0	0	0	0	0	0	0	0	1
	NASA	0	0	0	0	0	0	0	0	0	0	0	0	0
	Engine Manufacturer	0	0	1	1	1	0	1	1	0	1	1	1	0

		Market Criteria							Economic Criteria					Aircraft Design Criteria								
	Commercial Air Transport Design Stages	Vehicle Type and Size	Frequency of Service	Load Factor	Aircraft Required	Passengers Served	Carrier Expense and Revenue	Passenger Travel Time	Development Cost	Aircraft Unit Cost	Indirect Operating Cost	Direct Operating Cost	Return on Investment	Weight (OW and TOGW)	Speed	Number of Passengers	Cargo (Weight and Volume)	Takeoff and Landing Requirements	Range With Full Payload	Design Lifetime (Flying Hours and Number of Landings)	Noise (Passenger and Ground)	Handling Characteristics
Conceptual Design	Define General Size/Configuration	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	0	1	0	1	0
	Develop Layout, Plan Form and Inboard Profile	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	Define Wing Characteristics	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0
	Define Engine Parameters/Location	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	1	1	0	1	0
	Develop Gross Structural Configurations	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	0	0
	Analyze Static Stability and Control	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1
	Perform Preliminary Analysis of Costs and Manufacturing Feasibility	1	0	0	1	0	1	0	1	1	1	1	1	1	1	0	0	0	0	1	1	0
Preliminary Design	Perform Wind Tunnel Testing of "Best" Configuration	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0
	Perform Inlet/Wing/Airframe Matching	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	1	0
	Analyze Structural Design Loads, Aeroelastic Effects and Fatigue	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0
	Refine Weight Estimates	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
	Specify Jigs, Tooling, and Production Break Requirements	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
	Refine Cost Estimates	1	0	0	1	0	1	0	1	1	0	1	1	0	1	0	0	0	0	1	1	0
	Analyze Dynamic Stability and Control	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1
Detailed Design	"Freeze" Configuration	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
	Complete Detailed Structural Design	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
	Prepare Detailed Design and Production Drawings	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
	Produce Mockups of Interiors	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
	Design Jigs, Tools, and Production Fixtures	1	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
	Make Detailed Cost Estimates	1	0	0	1	0	1	0	1	1	0	1	1	0	1	0	0	0	0	1	0	0
	Specify Subsystem Equipment and Hardware	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
	Production Decision	1	0	0	1	0	1	0	1	1	0	1	1	1	1	0	0	0	0	0	0	0

	Design Criteria	Market Criteria							Economic Criteria					Aircraft Design Criteria								
	Decision Influencers	Vehicle Type and Size	Frequency of Service	Load Factor	Aircraft Required	Passengers Served	Carrier Expense and Revenue	Passenger Travel Time	Development Cost	Aircraft Unit Cost	Indirect Operating Cost	Direct Operating Cost	Return on Investment	Weight (OW and TOGW)	Speed	Number of Passengers	Cargo (Weight and Volume)	Takeoff and Landing Requirements	Range With Full Payload	Design Lifetime (Flying Hours and Number of Landings)	Noise (Passenger and Ground)	Handling Characteristics
Airframe Manufacturers	Board of Directors	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Executive Officer	1	0	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0
	Legal Director	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	Finance Director	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0
	Marketing Director	1	1	1	1	1	1	1	0	1	1	1	0	0	1	1	1	0	1	0	0	0
	Engineering Director	1	0	0	1	0	0	0	1	1	0	0	0	1	1	0	0	1	1	1	0	0
	Chief, Advanced Design	0	0	0	0	0	0	0	1	1	0	0	0	1	1	1	1	1	1	1	1	1
	Project Director	1	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	1	0	0
	Production Director	1	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0
	Chief, Manufacturing Development	1	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	1	0	0
	Airlines	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	0	1	1	0	0
	FAA/EPA	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	1	1	1
	Department of Commerce	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	Department of State	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Department of Defense	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	NASA	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	1	1	1
	Engine Manufacturer	1	0	0	1	0	0	0	0	1	0	1	1	1	1	0	0	1	0	0	1	0

FIGURE A-2. INTERACTIONS BETWEEN BARRIERS TO INNOVATION, DECISION INFLUENCERS, DESIGN CRITERIA, AND COMMERCIAL AIR TRANSPORT DESIGN AND DEVELOPMENT STAGES

REPRODUCIBILITY OF THE

Commercial Jet Engine Design and Development Stages

		Preliminary Design								Exploratory Development				Advanced Development					Engineering Development		Preliminary Design		Exploratory Development		Advanced Development		Engineering Development		All Design and Development Stages	
	Decision Influencers	Evaluate Market Forecasts	Define Engine Size and Cycle	Develop Conceptual Design of Engine Configuration	Estimate Engine Weight	Estimate Engine Costs (Production)	Perform IOC, DOC, and ROI Analyses	Perform Tradeoffs	Define Derivative Engines	Select Potential Technologies	Develop Alternative Technologies	Develop Alternative Components	Test and Evaluate Components	Demonstrate Alternative Technologies/Components	Test Alternative Components on Slave Engines	Perform Component Integration Tests	Evaluate Alternative Engine Technologies and Components	Develop Flight Engine Configured Mockups	Develop Demonstrator Engine	Perform Qualification Tests & Make Production Decision	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Engine Manufacturers	Board of Directors	2	1	0	0	3	1	1	1	0	1	1	0	1	0	0	1	0	2	0	9	6	2	5	2	10	2	6	15	6
	Executive Officer	2	1	0	0	4	2	2	3	0	1	1	0	1	0	1	2	1	4	1	14	3	2	5	5	5	5	4	26	4
	Legal Director	1	1	0	0	1	1	1	1	0	0	0	0	0	0	0	1	0	0	0	6	9	0	11	1	13	0	11	7	11
	Finance Director	2	1	0	0	3	1	1	1	0	1	1	0	1	0	0	1	0	2	0	9	6	2	5	2	10	2	6	15	6
	Marketing Director	1	1	1	0	2	3	1	1	0	0	0	0	0	0	0	1	1	2	0	10	4	0	11	2	10	2	6	14	8
	Chief, Engineering	0	1	1	1	0	1	2	2	2	2	2	3	2	2	4	4	2	4	4	8	8	9	1	14	1	8	1	39	1
	Manager, Preliminary Design & Development	0	0	0	0	0	0	2	2	1	1	1	1	1	1	2	2	0	0	2	4	10	4	2	6	2	2	6	16	5
	Project Director	0	1	1	0	0	1	0	0	0	0	0	1	0	0	1	1	2	3	1	3	11	1	10	4	6	4	5	12	9
	Strategic Planning Director	1	2	0	0	1	2	2	2	0	0	0	0	0	0	0	0	0	0	0	10	4	0	11	0	14	0	11	10	10
	Manager, Manufacturing Services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	11	0	14	0	11	0	15
	Airlines	2	3	2	0	1	5	3	4	1	0	0	1	0	0	2	2	2	4	3	20	1	2	5	6	2	7	2	35	2
	FAA/EPA	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	12	0	11	3	7	1	10	5	14
	Department of Commerce	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	11	0	14	0	11	0	15
	Department of State	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	11	0	14	0	11	0	15
	Department of Defense	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	13	4	2	3	7	0	11	7	11
	NASA	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	13	4	2	3	7	0	11	7	11
	Airframe Manufacturers	2	3	2	0	1	4	3	4	1	0	0	1	0	0	2	2	2	3	3	19	2	2	5	6	2	6	3	33	3

FIGURE A-3. INTERACTION OF DECISION INFLUENCERS WITH COMMERCIAL JET ENGINE DESIGN AND DEVELOPMENT (SCORING AND RANK ORDER OF IMPORTANCE OF DECISION INFLUENCERS BY DESIGN STAGE AND OVER ALL STAGES IS SHOWN IN COLUMNS AT RIGHT)

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Commercial Air Transport Design Stages

		Conceptual Design							Preliminary Design							Detailed Design								Conceptual Design		Preliminary Design		Detailed Design		Production		All Design and Development Stages	
	Decision Influencers	Define General Size/Configuration	Develop Layout, Plan Form and Inboard Profile	Define Wing Characteristics	Define Engine Parameters/Location	Develop Gross Structural Configuration	Analyze Static Stability and Control	Perform Preliminary Analysis of Costs and Manufacturing Feasibility	Perform Wind Tunnel Testing of "Best" Configuration	Perform Inlet/Engine/Airframe Matching	Analyze Structural Design Loads, Aeroelastic Effects and Fatigue	Refine Weight Estimates	Specify Jigs, Tooling, and Production Break Requirements	Refine Cost Estimates	Analyze Dynamic Stability and Control	"Freeze" Configuration	Complete Detailed Structural Design	Prepare Detailed Design and Production Drawings	Produce Mockups of Interiors	Design Jigs, Tools, and Production Fixtures	Make Detailed Cost Estimates	Specify Subsystem Equipment and Hardware	Production Decision	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Airframe Manufacturers	Board of Directors	1	0	0	0	0	0	2	0	0	0	0	1	2	0	0	0	0	0	1	2	0	2	3	14	3	14	3	14	2	12	11	14
	Executive Officer	4	0	0	0	1	0	5	0	0	1	0	3	5	0	0	0	0	0	4	5	0	5	10	11	9	11	9	10	5	6	33	11
	Legal Director	2	0	0	0	2	0	2	0	0	2	1	2	2	0	0	1	1	0	1	2	0	1	6	12	7	12	5	12	1	14	19	12
	Finance Director	2	0	0	0	0	0	3	0	0	0	0	1	3	0	0	0	0	0	2	3	0	3	5	13	4	13	5	12	3	10	17	13
	Marketing Director	12	0	2	4	3	1	7	2	2	2	0	2	6	1	0	0	0	0	3	6	0	6	29	3	15	8	9	10	6	4	59	7
	Engineering Director	7	1	3	3	6	2	7	3	3	4	2	4	6	2	1	2	2	1	4	6	1	6	29	3	24	1	17	1	6	4	76	2
	Chief, Advanced Design	8	1	3	4	5	3	6	3	4	3	2	2	5	3	2	2	2	2	2	4	2	4	30	2	22	2	16	5	4	7	72	3
	Project Director	5	0	1	1	4	1	9	1	1	3	2	3	7	1	1	2	2	1	3	7	1	7	21	7	18	6	17	1	7	1	63	5
	Production Director	4	0	0	0	3	0	5	0	0	2	2	3	4	0	1	2	2	1	3	4	1	4	12	9	11	9	14	6	4	7	41	9
	Chief, Manufacturing Development	4	0	0	0	3	0	5	0	0	2	2	3	4	0	1	2	2	1	3	4	1	4	12	9	11	9	14	6	4	7	41	9
	Airlines	13	0	2	4	5	1	9	2	2	3	2	3	7	1	1	2	2	1	3	7	1	7	34	1	20	3	17	1	7	1	78	1
	FAA/EPA	5	1	2	3	5	3	5	2	3	4	2	2	4	3	2	2	2	2	1	3	2	3	24	6	20	3	14	6	3	10	61	6
	Department of Commerce	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1	2	15	1	15	2	15	1	14	6	15
	Department of State	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	16	0	16	0	16	0	16
	Department of Defense	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	16	0	16	0	16	0	16
	NASA	3	1	2	3	4	3	4	2	3	3	2	1	3	3	2	2	2	2	0	2	2	2	20	8	17	7	12	9	2	12	51	8
	Engine Manufacturer	6	1	2	3	4	2	8	2	3	3	0	2	7	2	2	1	1	2	3	6	2	7	26	5	19	5	17	1	7	1	69	4

FIGURE A-4. INTERACTION OF DECISION INFLUENCERS WITH COMMERCIAL AIR TRANSPORT DESIGN (SCORING AND RANK ORDER OF IMPORTANCE OF DECISION INFLUENCERS BY DESIGN STAGE AND OVER ALL STAGES IS SHOWN IN COLUMNS AT RIGHT)

FOLDOUT FRAME

		Commercial Jet Engine Design and Development Stages																			Aggregated Levels of Interaction of Barriers to Innovation and Rank Order of Relative Importance									
		Preliminary Design								Exploratory Development				Advanced Development					Engineering Development		Preliminary Design		Exploratory Development		Advanced Development		Engineering Development		All Design and Development Stages	
	Barriers to Innovation	Evaluate Market Forecasts	Define Engine Size and Cycle	Develop Conceptual Design of Engine Configuration	Estimate Engine Weight	Estimate Engine Costs (Production)	Perform IOC, DOC, and ROI Analyses	Perform Tradeoffs	Define Derivative Engines	Select Potential Technologies	Develop Alternative Technologies	Develop Alternative Components	Test and Evaluate Components	Demonstrate Alternative Technologies/Components	Test Alternative Components on Slave Engines	Perform Component Integration Tests	Evaluate Alternative Engine Technologies and Components	Develop Flight Engine Configured Mockups	Develop Demonstrator Engine	Perform Qualification Tests & Make Production Decision	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
General Technical Considerations	1 Due to the need for backup technologies, it is difficult to exploit new technology to enable radically different vehicle configurations to be developed to reduce life cycle cost	2	2	3	1	1	5	7	8	4	3	3	5	3	3	8	8	4	7	9	29	24	15	7	26	13	16	16	86	19
	2 Relatively small performance savings associated with any particular component combined with the need to take incremental steps in innovative design	0	1	1	1	0	1	4	4	3	3	3	4	3	3	6	6	2	4	6	12	36	13	14	20	20	10	33	55	29
	3 Rapid rate at which technology is changing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	50	0	51	0	50	0	51
	4 Time to implement technology on a production basis	2	4	3	2	1	6	7	8	5	4	4	6	4	5	10	9	4	8	10	33	17	19	3	32	4	18	12	102	11
	5 Long lifetime design requirement for commercial aircraft	0	2	2	1	0	2	4	4	4	4	4	6	4	4	8	7	4	7	7	15	34	18	4	27	12	14	24	74	24
	6 Time required to certify new technology	2	5	4	1	1	6	7	8	5	4	4	7	4	4	10	9	6	10	10	34	15	20	1	33	2	20	8	107	8
	7 Certifying the use of new technology by FAA for commercial aircraft	2	5	4	1	1	6	7	8	5	4	4	7	4	4	10	9	6	10	10	34	15	20	1	33	2	20	8	107	8
	8 Lack of low cost methods for composite structure fabrication and nondestructive testing	2	5	4	2	1	7	5	6	4	3	3	6	3	4	9	8	6	11	9	32	19	16	6	30	8	20	8	98	13
	9 Service time required to develop confidence for designer and customer acceptance of new technology	4	7	5	1	2	10	6	8	3	1	1	4	1	2	7	6	6	10	8	43	13	9	27	22	18	18	12	92	14
Engine Technology Considerations	10 Material characteristics	0	1	1	1	0	1	2	2	2	2	2	3	2	2	4	4	2	4	4	8	44	9	27	14	33	8	37	39	39
	11 Turbine cooling	4	3	1	1	7	4	5	6	2	4	4	3	4	2	5	7	3	10	5	31	21	13	14	21	19	15	20	80	20
	12 Blade manufacturability	0	1	1	1	0	1	2	2	2	2	2	3	2	2	4	4	2	4	4	8	44	9	27	14	33	8	37	39	39
	13 Foreign object impact resistance	2	4	3	2	1	6	5	6	3	2	2	4	2	3	7	7	4	8	8	29	24	11	20	23	15	16	16	79	21
	14 Bearing/rotor design	0	1	1	1	0	1	4	4	3	3	3	4	3	3	6	6	2	4	6	12	36	13	14	20	20	10	33	55	29
	15 Seal design	0	1	1	1	0	1	2	2	2	2	2	3	2	2	4	4	2	4	4	8	44	9	27	14	33	8	37	39	39
	16 Turbine stage loading	2	2	1	1	4	3	4	5	2	3	3	3	3	2	5	6	3	8	5	22	31	11	20	19	23	13	25	65	26
	17 Integrated nacelle design	2	4	3	1	1	5	7	8	4	3	3	5	3	3	8	8	4	7	9	31	21	15	7	26	13	16	16	88	18
	18 Disc containment	2	4	3	2	1	6	5	6	3	2	2	4	2	3	7	7	4	8	8	29	24	11	20	23	15	16	16	79	21
Economic Considerations	19 Lack of investment enthusiasm in a maturing industry (cash flow situation)	8	8	3	0	11	13	9	11	1	2	2	1	2	0	3	6	5	12	8	63	2	6	34	16	31	20	8	105	10
	20 Cost of demonstration programs	2	4	3	0	1	6	3	4	1	0	0	2	0	0	3	3	4	7	4	23	30	3	42	10	39	11	31	47	37
	21 Patent/license considerations	6	4	0	0	8	5	5	5	0	2	2	0	2	0	1	3	1	6	1	33	17	4	39	7	41	7	41	51	34
	22 Nonproprietary nature of results obtained through NASA's program	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	50	0	51	0	50	0	51
	23 Market uncertainty for type and quantity of new aircraft	3	3	0	0	5	4	4	5	0	1	1	0	1	0	1	2	1	4	1	24	29	2	44	5	43	5	42	36	43
	24 Financing of new production facilities when visibility is limited on aircraft procurements and rates	6	3	0	0	10	4	4	5	0	3	3	0	3	0	1	4	1	8	1	32	19	6	34	9	40	9	36	56	28
	25 Disposal or conversion of production facilities for conventional technology	4	3	1	0	7	4	3	4	0	2	2	1	2	0	2	4	3	9	2	26	27	5	38	11	38	11	31	53	32
	26 Disposal of existing production machinery that may not be fully amortized	2	1	0	0	3	1	1	1	0	1	1	0	1	0	0	1	0	2	0	9	42	2	44	2	48	2	46	15	46
	27 Cost of new technology installed in aircraft	9	11	7	1	11	17	12	15	4	4	4	6	4	2	10	13	10	22	12	83	1	18	4	39	1	34	1	174	1
	28 Lack of competition from other manufacturers in the use of new technology	5	8	6	1	4	13	9	11	4	2	2	5	2	2	8	9	7	13	10	57	7	13	14	28	11	23	7	121	5
	29 The cost of tooling at all stages of manufacturing sequence using new technology	2	2	1	0	3	2	1	1	0	1	1	1	1	0	1	2	0	2	0	12	36	3	42	4	44	2	46	21	45
	30 Lack of production machinery infrastructure to produce machinery for new technology	2	2	1	0	2	2	2	2	2	2	2	4	2	2	5	5	4	7	5	13	35	10	23	18	24	12	27	53	32
	31 Adequacy of materials supply infrastructure	0	1	1	0	0	1	0	0	0	0	0	1	0	0	1	1	2	3	1	3	48	1	48	4	44	4	44	12	48
Social Considerations	32 Airline reluctance to use new technology	5	7	5	0	4	12	7	9	3	1	1	3	1	1	5	5	5	9	6	49	11	8	32	17	29	15	20	89	16
	33 Public reaction to new technology	5	7	5	0	4	12	7	9	3	1	1	3	1	1	5	5	5	9	6	49	11	8	32	17	29	15	20	89	16
	34 Lack of trained maintenance personnel	4	8	6	1	2	11	8	10	4	2	2	6	2	2	9	9	8	14	11	50	9	14	12	30	8	25	5	119	6
	35 Lack of accumulated experience base with new technology	4	8	6	1	2	11	8	10	4	2	2	6	2	2	9	9	8	14	11	50	9	14	12	30	8	25	5	119	6
	36 Conservative designs avoiding risk (due to publicity afforded failure) may not exploit the potential advantages of new technology	7	8	4	0	7	12	9	12	2	1	1	2	1	0	5	7	5	11	7	59	6	6	34	18	24	18	12	101	12
	37 Lack of in-service demonstration as opposed to prediction of performance	4	6	4	0	2	8	6	9	2	0	0	2	0	0	4	4	4	7	6	39	14	4	39	12	37	13	25	68	25
	38 Liability considerations	7	8	4	0	6	11	8	10	2	1	1	2	1	0	4	6	4	9	6	54	8	6	34	15	32	15	20	90	15
	39 Lack of recognition of need for advancement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	50	0	51	0	50	0	51
	40 Lack of pressure from customers for more economical equipment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	50	0	51	0	50	0	51
	41 Difficulty in recruiting adequately trained designers, production personnel, etc., who can work with new technology	0	2	2	1	0	2	2	2	2	2	2	4	2	2	5	5	4	7	5	11	40	10	23	18	24	12	27	51	34
	42 Union objections to changing technology	4	4	0	0	6	5	5	6	0	1	1	0	1	0	1	3	1	4	1	30	23	2	44	6	42	5	42	43	38
	43 Lack of training of production workers	0	1	1	0	0	1	0	0	0	0	0	1	0	0	1	1	2	3	1	3	48	1	48	4	44	4	44	12	48
Management Considerations	44 Personal biases	6	8	5	1	6	12	10	13	4	3	3	5	3	2	9	10	7	15	11	61	3	15	7	31	5	26	2	133	2
	45 Personalities of decisionmakers and willingness to take risk	6	8	5	1	6	12	10	13	4	3	3	5	3	2	9	10	7	15	11	61	3	15	7	31	5	26	2	133	2
	46 Company traditions/personalities	6	8	5	1	6	12	10	13	4	3	3	5	3	2	9	10	7	15	11	61	3	15	7	31	5	26	2	133	2
	47 Program management structure – matrix versus hierarchical	2	3	2	1	4	4	4	5	2	3	3	4	3	2	6	7	5	11	6	25	28	12	19	23	15	17	15	77	23
	48 Historic design practices are favored	0	1	1	1	0	1	4	4	3	3	3	4	3	3	6	6	2	4	6	12	36	13	14	20	20	10	33	55	29
	49 NIH factors	0	1	1	1	0	1	2	2	2	2	2	3	2	2	4	4	2	4	4	8	44	9	27	14	33	8	37	39	39
	50 Lack of an identifiable product champion	2	1	0	0	3	1	1	1	0	1	1	0	1	0	0	1	0	2	0	9	42	2	44	2	48	2	46	15	46
	51 Time at which technology is considered to be "available" is vastly different for scientists, aircraft designers, and production specialists	1	3	3	1	2	5	3	3	2	2	2	4	2	2	5	5	4	7	5	21	32	10	23	18	24	12	27	61	27
	52 Lack of experience in production adds to uncertainty and risk	0	2	2	1	0	2	2	2	2	2	2	4	2	2	5	5	4	7	5	11	40	10	23	18	24	12	27	51	34
	53 Developing confidence of suppliers and customers that new technologies are sufficiently advanced to justify the use of new materials or processes	2	3	1	0	3	5	3	3	0	0	0	0	0	0	0	1	1	2	0	20	33	0	50	2	48	2	46	24	44
	54 Export controls (CoCom list)	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	50	4	39	3	47	0	50	7	50

FIGURE A-5. INTERACTION OF BARRIERS TO INNOVATION WITH COMMERCIAL JET ENGINE DESIGN AND DEVELOPMENT (SCORING AND RANK ORDER OF IMPORTANCE OF BARRIERS TO INNOVATION BY DESIGN STAGE AND OVER ALL STAGES IS SHOWN IN COLUMNS AT RIGHT)

FOLDOUT FRAME 2

FOLDOUT FRAME

Commercial Air Transport

Design Stages

		Conceptual Design						Preliminary Design								Detailed Design								Aggregated Levels of Interaction of Barrier to Innovation and Rank Order of Relative Importance									
	Barriers to Innovation	Define General Size/Configuration	Develop Layout, Plan Form and Inboard Profile	Define Wing Characteristics	Define Engine Parameters/Location	Develop Gross Structural Configuration	Analyze Static Stability and Control	Perform Preliminary Analysis of Costs and Manufacturing Feasibility	Perform Wind Tunnel Testing of "Best" Configuration	Perform Inlet/Engine/Airframe Matching	Analyze Structural Design Loads, Aeroelastic Effects and Fatigue	Refine Weight Estimates	Specify Jigs, Tooling, and Production Break Requirements	Refine Cost Estimates	Analyze Dynamic Stability and Control	"Freeze" Configuration	Complete Detailed Structural Design	Prepare Detailed Design and Shop Drawings	Produce Mockups of Interiors	Design Jigs, Tools, and Production Fixtures	Make Detailed Cost Estimates	Specify Subsystem Equipment and Hardware	Production Decision	Preliminary Design		Exploratory Development		Advanced Development		Engineering Development		All Design and Development Stages	
																								Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
General Technical Considerations	1 Due to the need for backup technologies, it is difficult to exploit new technology to enable radically different vehicle configurations to be developed to reduce life cycle cost	42	3	10	14	27	9	46	10	12	19	10	18	30	9	8	11	11	8	19	36	8	37	151	17	116	17	101	15	37	15	405	16
	2 Relatively small performance savings associated with any particular component combined with the need to take incremental steps in innovative design	4	0	0	0	3	0	5	0	0	2	2	3	4	0	1	2	2	1	3	4	1	4	12	48	11	48	14	48	4	48	41	48
	3 Rapid rate at which technology is changing	40	3	10	14	27	9	43	10	12	19	10	17	35	9	8	11	11	8	17	33	8	34	146	19	112	19	96	17	34	20	338	19
	4 Time to implement technology on a production basis	22	2	6	7	17	5	29	6	7	12	6	12	24	5	5	7	7	5	13	23	5	21	88	37	72	37	63	40	21	40	244	40
	5 Long lifetime design requirement for commercial aircraft	64	4	17	25	37	16	61	17	21	26	12	22	51	16	11	13	13	11	24	47	11	48	224	1	165	1	130	2	46	2	567	1
	6 Certifying the use of new technology by FAA for commercial aircraft	50	4	13	8	32	13	51	13	16	23	13	21	43	13	9	13	13	9	21	40	9	39	181	4	142	3	114	5	39	9	476	4
	7 Lack of low cost methods for composite structure fabrication and nondestructive testing	32	3	11	15	28	10	41	11	13	19	12	17	33	10	8	12	12	8	16	31	8	31	140	21	115	16	95	20	31	25	381	21
	8 Service time required to develop confidence for designer and customer acceptance of new technology	63	4	14	21	37	13	64	14	17	27	13	26	54	13	10	12	14	10	27	51	12	51	216	2	164	2	136	1	51	1	567	1
Airframe Technology Considerations (Composite Material)	9 Repair or replacement of composite structures after accident, e.g., fire	43	3	10	15	24	10	45	10	13	17	8	16	36	10	8	9	9	8	18	35	8	36	150	18	112	19	95	20	36	18	393	18
	10 Cost of establishing property matrix of composite material	20	2	7	8	15	6	22	7	8	10	6	9	18	6	4	6	6	4	9	17	4	17	80	42	64	42	50	42	17	44	211	42
	11 Interface of composites with metallic structures (e.g., complex, costly joints)	29	3	9	11	23	9	32	9	11	16	10	14	26	9	7	10	10	7	13	24	7	22	116	29	95	29	78	31	22	38	311	30
	12 Development of advanced design and manufacturing technologies for large airframe structures to reduce number of joints and fasteners, and hence, part count	29	3	8	11	23	9	32	9	11	16	10	14	26	9	7	10	10	7	13	24	7	22	116	29	95	29	78	31	22	38	311	30
	13 Direct substitution of parts (composite for metal) does not allow opportunity in design to exploit advantageous characteristics of composites	26	3	9	11	19	8	30	9	11	13	6	11	25	8	6	7	7	6	12	23	6	24	106	33	83	33	67	34	24	32	280	33
	14 Developing low cost methods for fabricating high-quality composite structures	20	3	7	9	17	7	24	7	9	12	8	10	20	7	6	7	7	6	10	18	6	19	87	41	71	41	60	41	19	41	237	41
	15 Excessive qualification testing and proof testing	47	5	15	21	33	15	40	15	19	23	12	17	39	15	11	13	13	11	16	35	11	30	184	3	140	5	110	9	30	26	464	7
(Active Control)	16 Development of system design requirements	38	3	11	15	25	10	36	11	13	17	10	14	29	10	7	10	10	7	13	27	7	27	139	23	104	26	81	28	27	30	350	26
	17 Improved preliminary design weight estimate and payoff methods	13	1	4	5	9	4	15	4	6	6	4	5	12	4	3	4	4	3	5	11	3	11	51	46	40	46	33	46	11	47	135	46
	18 Lack of demonstrated hardware reliability	47	3	11	15	28	10	48	11	13	20	11	21	41	10	7	11	11	7	21	39	7	38	162	11	127	9	103	14	38	13	430	12
Economic Considerations	19 Lack of investment enthusiasm in a maturing industry (cash flow situation)	55	2	10	15	26	7	56	10	11	18	8	22	48	7	6	9	9	6	27	51	6	48	171	8	124	11	114	5	48	2	457	8
	20 Cost of demonstration programs	50	4	13	18	29	12	54	13	16	20	10	20	46	12	9	11	11	9	23	43	9	44	180	5	137	6	115	4	44	6	476	4
	21 *Patent/license considerations*	14	2	4	6	10	5	18	4	6	8	3	6	16	5	4	4	4	4	7	14	4	12	59	44	48	43	41	45	12	45	160	44
	22 Nonproprietary nature of results obtained through NASA's program	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	50	0	50	0	50	0	50
	23 Market uncertainty for type and quantity of new aircraft	54	2	10	15	26	7	55	10	11	18	8	22	47	7	6	9	9	6	26	46	6	47	169	9	123	12	108	11	47	5	447	9
	24 Financing of new production facilities when visibility is limited on aircraft procurements and rates	29	2	6	7	18	5	39	6	7	13	6	17	34	5	5	7	7	5	20	33	5	34	106	33	88	32	82	27	34	20	310	32
	25 Disposal or conversion of production facilities for conventional technology	32	2	6	7	21	5	42	6	7	15	8	18	36	5	6	9	9	6	22	35	7	36	115	31	96	27	84	23	36	18	341	28
	26 Disposal of existing production machinery that may not be fully amortized	16	1	2	3	8	2	21	2	3	6	2	9	18	2	3	3	3	3	12	18	3	19	53	45	43	45	45	43	19	41	160	44
	27 Cost of new technology installed in aircraft	50	2	10	15	26	8	49	10	11	18	10	20	41	8	6	10	10	6	22	40	6	38	160	13	118	16	100	16	38	13	416	15
	28 Lack of competition from other manufacturers in the use of new technology	47	3	11	15	30	9	49	11	13	20	12	20	40	9	9	12	13	9	21	38	9	39	164	10	125	10	112	8	39	9	440	10
	29 The cost of tooling at all stages of manufacturing sequence using new technology	22	2	6	7	17	5	29	6	7	12	6	12	24	5	5	7	7	5	13	23	5	24	88	37	72	37	65	36	24	32	249	37
	30 Lack of production machinery infrastructure to produce machinery for new technology	22	2	6	7	17	5	29	6	7	12	6	12	24	5	5	7	7	5	13	23	5	24	88	37	72	37	65	36	24	32	249	37
	31 Adequacy of materials supply infrastructure	22	2	6	7	17	5	29	6	7	12	6	12	24	5	5	7	7	5	13	23	5	24	88	37	72	37	65	36	24	32	249	37
Social Considerations	32 Airline reluctance to use new technology	43	2	10	15	22	7	40	10	11	15	6	14	33	7	5	7	7	5	16	32	7	29	139	22	96	27	79	30	29	27	343	27
	33 Public reaction to new technology	17	0	2	4	6	1	14	2	2	4	2	6	12	1	1	2	2	1	7	12	1	12	44	47	29	47	26	47	12	45	111	47
	34 Lack of trained maintenance personnel	30	2	8	11	20	7	30	8	9	14	8	12	24	7	5	8	8	5	11	23	5	23	108	32	82	35	65	36	23	37	278	35
	35 Lack of accumulated experience base with new technology	41	4	13	18	29	13	40	13	16	20	12	16	32	13	9	12	12	9	13	29	9	29	158	14	121	13	93	24	29	27	401	17
	36 Conservative designs avoiding risk (due to publicity afforded failure) may not exploit the potential advantages of new technology	26	3	9	11	19	8	30	9	11	13	6	11	25	8	6	7	7	6	12	23	6	24	106	33	88	33	67	34	24	32	280	33
	37 Lack of in service demonstration as opposed to prediction of performance	39	2	8	11	23	7	42	8	9	17	9	19	36	7	5	9	9	5	19	35	5	34	132	26	105	24	87	26	34	20	358	24
	38 Liability considerations	49	4	12	17	31	12	54	12	15	23	11	22	46	12	9	12	12	9	22	43	9	43	178	6	141	4	116	3	43	7	478	3
	39 Lack of recognition of need for advancement	23	1	4	7	10	3	22	4	5	7	2	8	19	3	3	3	3	3	10	18	3	19	70	43	48	43	43	44	19	41	180	43
	40 Lack of pressure from customers for more economical equipment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	50	0	50	0	50	0	50
	41 Difficulty in recruiting adequately trained designers, production personnel, etc., who can work with new technology	25	2	3	7	19	6	31	3	7	14	8	15	26	6	5	8	8	5	15	25	5	25	93	36	79	30	71	33	25	31	268	38
Management Considerations	42 Personal biases	41	2	8	11	25	6	45	8	8	18	9	20	38	6	6	10	10	6	21	37	6	37	138	23	108	22	96	17	37	15	379	22
	43 Personalities of decisionmakers and willingness to take risk	40	2	8	11	24	6	45	8	9	17	9	19	38	6	6	10	10	6	20	37	6	37	136	25	106	23	95	20	37	15	374	23
	44 Company traditions/personalities	56	2	10	16	28	7	57	10	11	20	9	24	49	7	6	10	10	6	27	48	6	48	175	7	130	7	113	7	48	2	486	6
	45 Program management structure — matrix versus hierarchical	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	50	0	50	0	50	0	50
	46 Historic design practices are favored	46	3	10	14	30	9	50	10	12	22	11	22	42	9	8	12	12	8	22	40	8	40	162	11	128	8	110	9	40	8	440	10
	47 NIH factors	30	3	9	11	22	8	35	9	11	15	8	14	28	8	7	9	9	7	15	27	7	28	118	28	94	31	81	28	28	29	321	29
	48 Lack of an identifiable product champion	38	2	8	11	24	7	40	8	9	17	10	18	33	7	6	10	10	6	18	32	6	32	130	27	102	26	88	25	32	24	352	25
	49 Time at which technology is considered to be "available" is vastly different for scientists, aircraft designers, and production specialists	44	3	10	14	28	9	48	10	12	20	10	20	40	9	8	11	11	8	21	38	8	39	156	15	121	13	105	12	39	9	421	13
	50 Lack of experience in production adds to uncertainty and risk	40	3	10	14	27	9	43	10	12	19	10	17	35	9	8	11	11	8	17	33	8	34	146	19	112	19	96	17	34	20	388	19
	51 Developing confidence of suppliers and customers that new technologies are sufficiently advanced to justify the use of new materials or processes	44	3	10	14	28	9	48	10	12	20	10	20	40	9	8	11	11	8	21	38	8	39	156	15	121	13	105	12	39	9	421	13
	52 Export controls (CoCom list)	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1	2	49	1	49	2	49	1	49	6	49

FIGURE A-6. INTERACTION OF BARRIERS TO INNOVATION WITH COMMERCIAL AIR TRANSPORT DESIGN (SCORING AND RANK ORDER OF IMPORTANCE OF BARRIERS TO INNOVATION BY DESIGN STAGE AND OVER ALL STAGES IS SHOWN IN COLUMNS AT RIGHT)

FOLDOUT FRAME 2

APPENDIX B

TECHNICAL CONSIDERATIONS FOR INTRODUCING ADVANCED COMPOSITES INTO CIVIL TRANSPORT AIRFRAMES

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Brief Historical Perspective

The first application of composite materials to aircraft primary structures in the United States, was the fuselage of the Vultee BT-15. This was a single-engined, low-wing monoplane designed, fabricated, and tested in the laboratory by the U.S.A.A.F. in 1943. The first flight was in March, 1944. On a strength-to-weight basis, the fuselage which was in sandwich construction with glass-reinforced plastic (GRP) skins and an end-grain balsa core, showed a 50 percent improvement over the conventional aluminum structure. Around the same time, the U.S.A.A.F. designed and fabricated a wing for the North American AT-6, also a single-engined, low-wing monoplane. This structure was also of sandwich design, but the GRP skins were stabilized by a cellular, cellulose-acetate core. While both composite structures demonstrated a significant improvement in static strength over aluminum structures, the designs did not enter production. The principal problems which hindered the production go-ahead of these structures, were, briefly, as follows:

- Lack of automated fabrication methods to produce reliable structures (hand-layup was used)
- Limited knowledge on the effects-of-defects and, hence, there was little basis for confidence in the design
- The cost-estimates were questionable and, hence, doubts existed on projected cost-competitiveness.

There are further examples where attempts to employ composites in production primary airframe structures failed for these and similar reasons. However, the use of GRP for radomes was most successful where the unique electrical characteristics could be utilized.

International Considerations

An important consideration when evaluating and justifying composite materials for civil aircraft primary structure applications is the bilateral and multilateral consortiums which are being established between U.S. and foreign manufacturers. With the exception of possibly rotor-blade fabrication, the United States is, at least, 4 years ahead of most Western countries with primary composite structure applications in both military and civil aircraft and, neither the design capabilities nor the manufacturing facilities for advanced composites are available in the foreign countries to produce large primary structures for civil transport or military aircraft. The technology being developed under NASA and DOD sponsorship is important since it should provide the United States with a more commanding position and, therefore, leverage when negotiating future international agreements. These agreements usually require major components and/or subassemblies to be fabricated in the countries where head offices of potential airline customers are located. The composite technology under development will enable the United States to compete favorably, and it is likely that the composite structures will have to be produced in this country. Due to the projected growth of composites where over 2.5 million flight hours will have been logged by composite components by 1982(1) and the projected 26 percent weight savings with composite-wings(2), this competitive edge is important.

Design Staff Limitations

The relatively small, but effective, design teams established to develop experimental aircraft structures will need to be considerably expanded when a commitment is made to introduce composite structures into series production. When one considers a major program with tight schedules required to meet market opportunities, over 2,000 engineers are needed to release the drawings on a typical aircraft and then 800 engineers might be retained throughout the duration of the program to incorporate modifications which are constantly introduced. It would appear that implications of building larger staffs, experienced in composites, should be recognized already at this time. Aerospace companies are capable of retraining engineers on-site and several have impressive in-house educational programs.

In all aerospace companies, experienced designers recruited during World War II and in the early 1950's, are now retiring. This represents a loss of extensive experience. Because of the problem of the high average age of design staffs, there is a need to hire and train new generations of designers in the next 5 to 10 years. Recently NASA awarded a grant to Rensselaer Polytechnic Institute to establish a center for the study of composite material applications to energy efficient aircraft. This is a timely and important step which will help to reduce the effect of the above problems.

The technology transfer process can be simplified by having key composite engineers "walk" with the aircraft development, i. e., from the conceptual through detail design stages. Furthermore, to achieve low-cost designs, the designers must become involved in the shops to help identify high-cost areas in manufacturing and assembly and to assist in developing solutions involving manufacturing technologies. This is an important interface.

Recent Important Developments in Structures Technology for Military Aircraft

The use of advanced composites for the Navy F-14, the Air Force F-15 horizontal stabilizers in production, and similar parts for the F-16 have been well documented. The results of this impressive service experience with the F-14 and F-15 and the confidence thus being acquired, are now being applied in major components for the Rockwell International B-1. Besides offering cost savings and considerable weight savings, other advantages of employing advanced composite materials for the F-14, F-15, and F-16 stabilizers should be mentioned. Composites are built up-to-shape, rather than being machined down-to-shape, as is frequently the case with metals resulting in low-utilization factors(3). Furthermore, long lead-times are required for the dies of large forgings and the machining operation itself is expensive. Composites should enable lead-times to be reduced circumventing some traditional production problems and will provide the designer with more time to, for example, conduct manufacturing cost/design trades, and with greater flexibility in the development process. The military experience is, of course, important for civil aircraft composite acceptance.

During a visit to the Boeing Commercial Airplane Company, it was stated that structural developments on the Air Force YC-14 STOL transport will result in technologicals spinoff for their future civil transport designs. Two specific examples were mentioned; the electronic cockpit displays and the bonded honeycomb sandwich construction used for the horizontal and vertical stabilizers. The sandwich structural configuration is frequently employed for composites. The YC-14 structure is an important development of advanced primary structures, as adhesive-bonding is extensively used. Adhesive-bonding is, of course, sometimes employed between metallic and composite components, besides for joining the composite elements themselves. Boeing has acquired extensive experience in the application of adhesive-bonded honeycomb and also low-cost GRP composites in secondary structures on all 707 civil aircraft and military versions of this aircraft. The selection of bonding for the YC-14 was a projection of this experience. In several instances on the YC-14, lower cost design approaches were used to alleviate the problem of traditional cost drivers. Machining of the honeycomb core was minimized and simple, but efficient, edge-member designs were developed. However, Boeing is anticipating some problems with the Air Force Logistics Command (AFLC) because of limited experience in repairing sandwich primary structures.

The primary adhesive-bonded structure (PABST) under development at McDonnell-Douglas Corporation is a further example of potential spin-off from military aircraft to civil transports. The objectives of this fuselage program sponsored by U.S.A.F. are to save 20 percent in manufacturing cost and 20 percent in life-cycle cost, which implies increased inspection intervals and/or reduced repair costs. These objectives provide a further indication of the importance of design-to-cost prevailing in all programs.

Primary Structures - Some Economic Considerations

The limited service experience with civil transport primary structures must be supported by extensive laboratory tests and analytical modeling of the effect of defects, derived during fabrication and in service, to enable the data to be transferred from one structure to another type. While the introduction of composites should not influence flight-test time, all companies visited by the project team expressed concern about the excessive cost per hour of flight-testing. This cost is approximately $30,000 per hour and a total of 1,000 hours are probably required for the four aircraft that are normally flight tested. This cost represents flight-time only. Furthermore, a large group of engineers is also required to analyze the data. The economic and other resources needed for this phase of civil transport development must serve as a drain on those funds required to transfer or commit new materials, manufacturing and other technologies into series production aircraft.

A further factor to consider with the development of composite structures for civil transports is the implication of airline cost of ownership and operation as they apply to guarantees and the losses which an airframe manufacturer might incur.

Consideration of the airline maintenance requirements and repair procedures for composite materials must be included at the design phase, as airline labor maintenance costs are increasing and productivity is decreasing. Hence, airlines will be concerned even more than in the past about the cost of maintenance for both provisional and major repairs. Furthermore, airline maintenance departments seem to be reducing in size, yet the staff which is available must be trained to repair these new materials and structures which have different configurations and joints than metallic assemblies. New techniques for inspection and repair are necessary which require further investments by the airlines and should also be developed with cost in mind. Design for insensitivity of the structure to material and fabrication deficiencies must also receive consideration in the overall effort by design-manufacturing teams to reduce cost.

The cost of composite structures are frequently compared with metallic structures already in production. In this case, the metallic components have usually arrived at an advanced point on the learning curve and the costs of the two types of structure may, therefore, never intersect. Because of this advantage, structure in production might always be of lower cost. When substituting composite materials for metallic hardware in production, composite structures can be in an unfavorable position when the final decisions are being made by management in consultation with the airlines. On the other hand, advanced composites represent a new technology for civil aircraft and will therefore attract considerable attention. This could result in a steeper learning curve. The higher cost of the composite material will result in a significant effort to compensate for this by reducing the part-count, quality control costs, and hence, manufacturing and assembly manhours for demonstration hardware. Because of these potential cost problems, candidate structures for demonstrating composites must be selected with considerable care.

A major problem with organic composites is the difficulty in optimized primary structural configurations to provide an alternative metallic structure or backup technology which will meet the form, fit, and function requirements of the composite should a major economic or technical problem occur. Joints in composite structures, for example, are different than for other materials. Should such a drastic change be necessary, slippage of the civil transport delivery schedules will unfavorably influence the market opportunities. This can be a difficult financial problem for both the airframe manufacturer and the airline customer.

Primary structures of civil transport aircraft require a 10- or 12-year warranty. The annual utilization and life expectancies of civil and military aircraft are shown in Table B-1. With regard to warranties, a wing-box or a horizontal stabilizer-box represent different problems than flaps or other control surfaces which can be easily segmented, providing redundancy, and replaced. Current civil transport wings and stabilizer panels are relatively low-cost structures. The airlines may not readily accept an aircraft with a unique major structure without significant cost savings and appropriate warranties which are already a major burden for the aircraft manufacturer. The Government should, therefore, continue their support of programs designed to accelerate technology transfer, but it must be kept in mind that the extensive application of new technologies, for example, composite materials, will be cautiously considered by the manufacturers for reasons such as the service-warranty risks involved. Consequently the application of technologies whose development is supported by Government funding may be delayed in spite of the success being demonstrated in the current programs.

TABLE B-1. ADVANCED COMPOSITE APPLICATIONS, ANNUAL USAGE AND LIFE EXPECTANCIES OF SELECTED AIRCRAFT

Aircraft Type	Advanced Composite	Weight per Ship-Set	Annual Usage, Hours	Life Expectancy, Hours
F-14*	Boron/Epoxy	185	350	4,000
F-15**	Boron/Epoxy & Graphite/Epoxy	210 100	350	4,000
707-300C	-	-	3,500	30,000
747-100	-	-	3,500	60,000

*F-14 employs advanced composites in empennage.
**F-15 employs advanced composites in empennage and speed brake.

Fabrication Technology - A Weak Link Due to Cost?

While minimized life-cycle costs have always been of importance to the airframe manufacturers and the airlines, in the future, increased emphasis can also be expected to reduce acquisition cost due to the investment alternatives that are available for capital. It is, therefore, necessary to continue to further develop strong materials/manufacturing/design interfaces from the outset of all programs to reduce these costs while achieving acceptable or affordable structural performance. Equipment is needed to fabricate, inspect, and assemble the structures at lower costs. Also, innovative design concepts must be evolved for ease of fabrication and ease of nondestructive evaluation. It is likely, that today a composite fin, using state-of-the-art design and fabrication techniques, would cost more than a production fin in aluminum alloy. For example, an aluminum fin for a wide-bodied jet probably costs between $50,000 and $60,000. However, the cost-saving possibilities of graphite-cloth versus the tape form are important in this regard. The selection of cloth, tape, epoxies, or thermoplastics will, of course, depend on the structural part being designed. A potential problem with composite tape-laying equipment is that companies producing such equipment are experiencing financial problems. This factor needs consideration, for example, by stimulating commercial uses of the facilities.

As the airlines are emphasizing, firstly, economics; secondly, energy; and thirdly, environment, the designers must generate lower cost structures with regard to both acquisition cost and the cost of operation. Economy is the main objective.

Summarizing, energy efficient civil aircraft require not only the the development of composite structures, but also the specialized equipment required for their fabrication and nondestructive evaluation.

Secondary Structures - A Logical Opportunity for Composites

Secondary structures seem to offer an important opportunity for composite materials, in particular graphite-reinforced thermoplastic sheets and chopped fibers and also, novel fabrication techniques such as braiding, molding, pultrusion, and weaving. Secondary structures are frequently cost-drivers in aircraft construction. As briefly mentioned earlier, some major components of primary structures such as the wing slabs, are the lowest cost form of construction, e.g., the formed, primed, and machined skins for wide-body jets may cost as low as $8.00 per pound prior to assembly. The lowest cost per pound is frequently achieved with structures subjected to the greatest loads such as the landing gear and wing panels. This is due to the higher working stress levels and lower part count(4). Furthermore, the weight of secondary structures is frequently almost identical to those of assembled primary structures and is shown in Table A-2. This table was compiled from discussions at the Lockheed-California Company, Burbank, California.

Graphite-reinforced thermoplastics (G/Tp) available in the form of sheet materials can be stored in a similar way to metal sheets and are suited to high-volume forming processes. G/Tp is being studied by the Boeing Company for clips, fittings, and ribs. Because of the advantages of graphite/thermoplastics, they are expected also to make important inroads in consumer products, such as in automobiles. Commercial applications are not only important with regard to potential reduction of material costs attributed to increasing the volume of materials produced, but also because the fabrication processes developed for consumer products are expected to be applicable, in certain cases, to the aerospace industry. The designer may find it desirable to develop families of standard brackets, riblets, etc, for secondary structures that lend themselves to the utilization of these new fabrication processes and, hence, reduce cost.

A further point concerning the use of composites for secondary structures is that the glass-reinforced preimpregnated plastics already extensively used for fairings, control surfaces, etc, can be conveniently

TABLE B-2. APPROXIMATE PERCENTAGE WEIGHT DISTRIBUTIONS OF PRIMARY AND SECONDARY STRUCTURES IN A WIDE-BODY CIVIL AIRCRAFT.*

Structure Category	Major Sub-Assembly		
	Fuselage	Wing	Empennage
Primary	70%	50%	50%
Secondary	30%	50%	50%

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* Table prepared from discussions at the Lockheed-California Company.

selectively reinforced or "spiked" using grids of graphite-fibers in the weave for application in, for example, critical joining areas. While graphite-fibers will never be as inexpensive as glass-fibers, the selective reinforcement of these laminates, where a minimum gage problem does not exist, may enable thinner laminates to be used. In commercial products, reductions in layup time have compensated for the higher cost of the graphite fibers, besides providing the required structural strength, stiffness, and fracture tolerance. Introducing graphite fibers in components already extensively employing glass-fiber reinforced plastics (GRP) is important, as the airlines will begin to acquire experience with this new material in a form familiar to them. Most airlines have engineers and technicians experienced with low-cost GRP. The Boeing-747, today, utilizes over 12,000 square feet of GRP which has been accepted and successfully maintained by the airlines for several years. The incorporation of the graphite-fiber grid will not increase maintenance costs for the airlines, on the other hand, these requirements should be reduced.

An unpredictable yet major cost for the airlines with secondary structures is the problem of corrosion control and repair in cargo holds, galleys, and lavatories. Composite materials will minimize corrosion problems, besides reducing the weight and acquisition costs mentioned earlier. These, then, are a number of important reasons why secondary structural applications of advanced composites should continue to be pursued and possibly even expanded by NASA.

The Design-to-Lowest Cost Problem

It was evident during the visits to the civil aircraft companies, that the challenge of designing to lowest cost are expected to become increasingly severe due to the growing problems of inflation, systems sophistication, fuel costs, labor costs, and other business opportunities competing for available funds. It is therefore necessary that the benefits of new technologies be justified not only by performance improvements, for example, by providing new aerodynamic configurations made possible by these materials and processes, but also by alleviating these problems of designing to lowest cost. The design teams at the commercial airplane companies are being motivated into a design-to-cost attitude by providing(5)

- Incentive-cost targets against which personnel performance can be measured
- Tools - documentation of costs and cost reduction methods.

The aircraft design team priorities are shown in Figure B-1, and in Figure B-2, the interaction is shown between manufacturing costs of <u>all</u> types of structures and design objectives, which includes life-cycle costs. These figures were provided by the Boeing Commercial Airplane Company; a member of the Battelle/airframe industry team preparing Reference 5.

It is evident that the designers must consider cost as a design parameter and a design discipline along with weight and performance, Figure 3(6). Every decision requires a thorough understanding of all costs involved but to meet the requirements of the design to lowest cost approach, the personnel on each program will be dedicated to reducing costs. It is necessary to provide detailed information on all aspects of the cost of composite materials to designers. The data must be presented in a manner familiar to him so he can use it rapidly and develop confidence in it as with metals. Design information of this type is being developed for metallic materials(5). The designer will be expected to understand all costs centers and must conduct various cost trades between metallic and composite materials when making selections of materials, manufacturing technologies, and developing lowest-cost configurations.

It is essential that management and the designers be provided with cost information on all aspects of composite material development in the following areas:

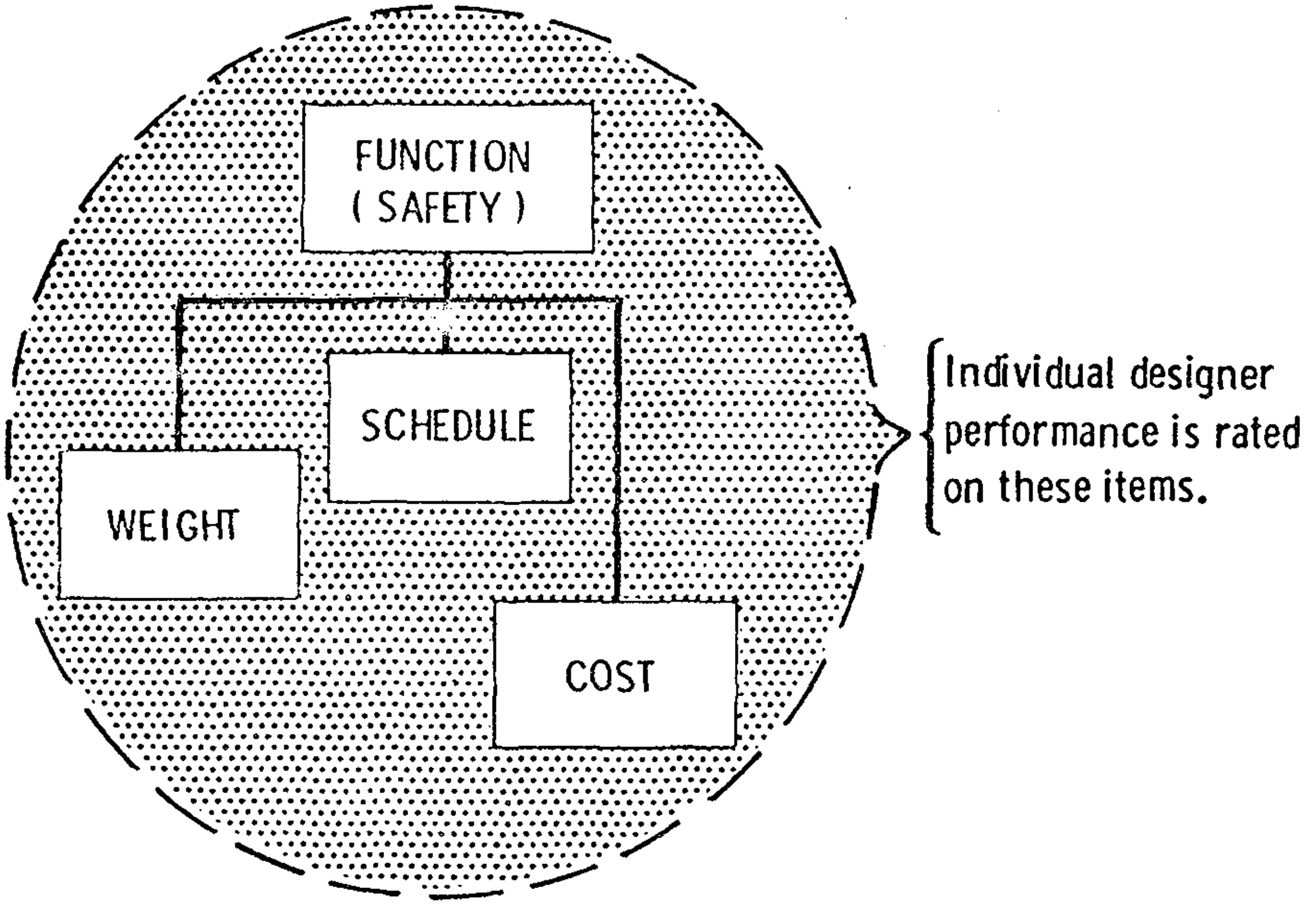


FIGURE B-1. PRESENT AIRCRAFT DESIGN TEAM PRIORITIES(5)

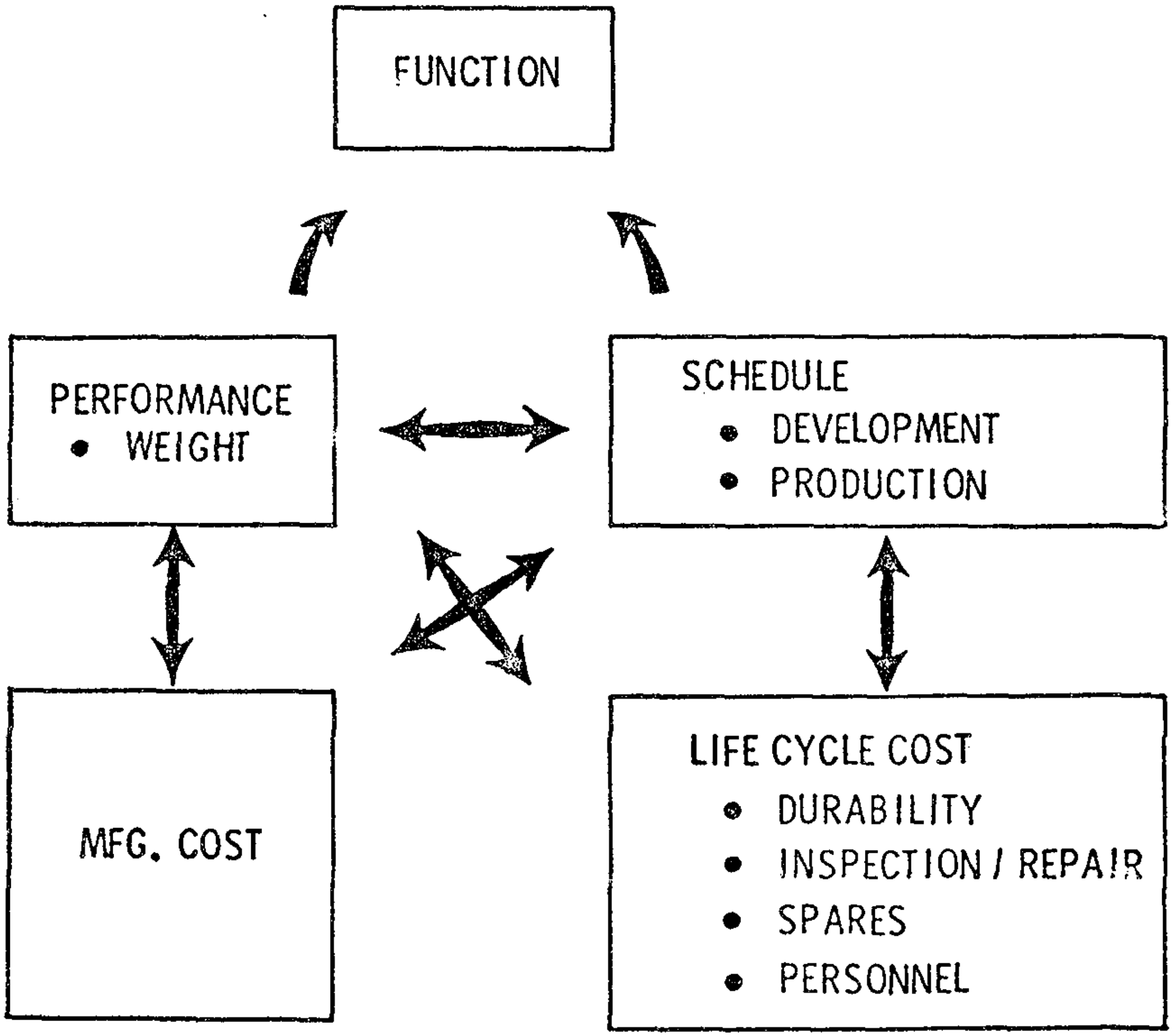


FIGURE B-2. INTERACTIONS BETWEEN DESIGN DISCIPLINES(5)

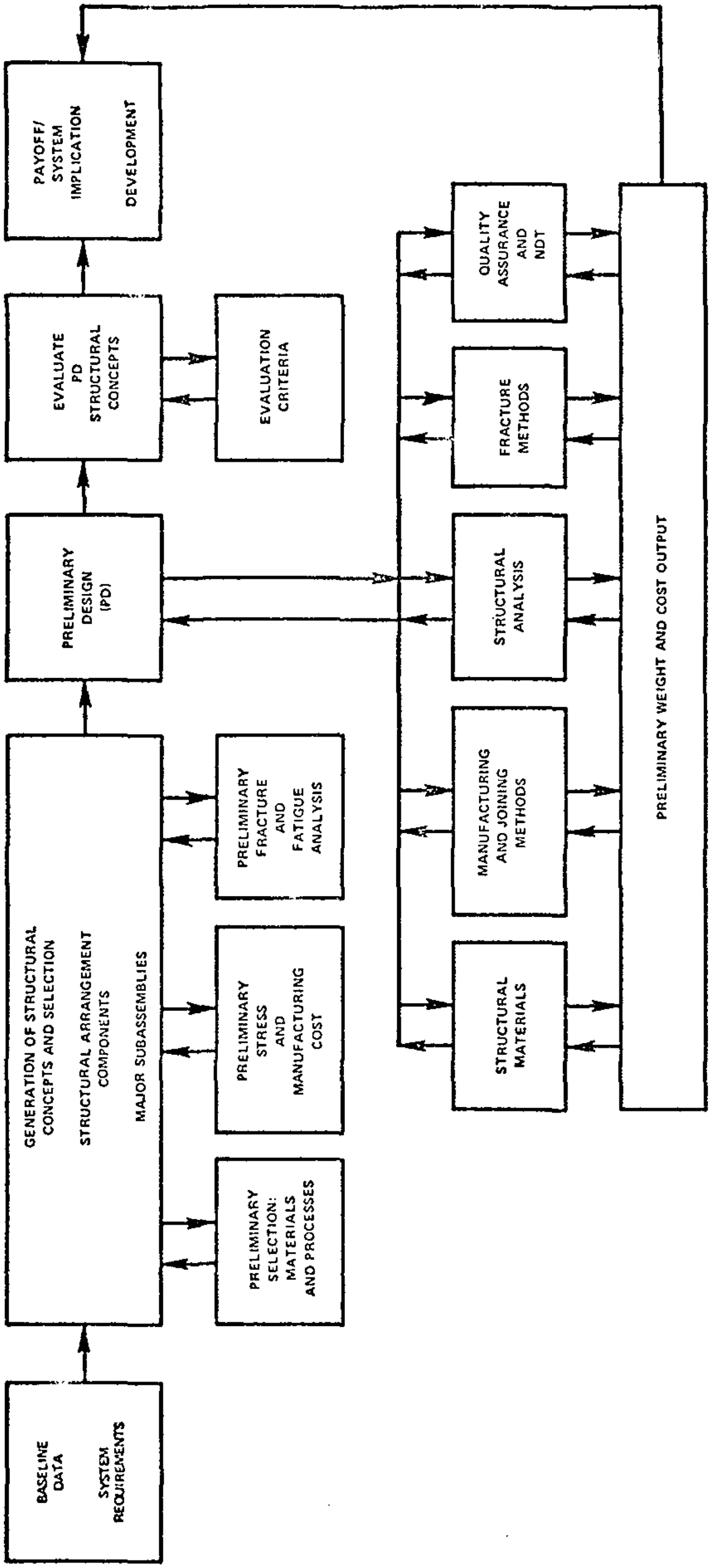


FIGURE B-3. ADVANCED MATERIALS AND STRUCTURES PAYOFF ASSESSMENT(6)

- Material property generation
- Fundamental material fabrication processes
- Component fabrication methods
- Methods of analysis
- Joining and assembly technologies
- Nondestructive evaluation (NDE)
- Serviceability and repair, etc.

All programs on composite material structure development for commercial airframes must include cost studies on the various aspects of composite design, fabrication, assembly, and serviceability in addition to the traditional studies on structural performance, damage tolerance, etc.

The variation of the cost reduction leverage with time for airframe designers at various points in the design process is indicated in Figure B-4. It is seen that the opportunities to reduce cost and improve the structural performance varies drastically throughout the design/production cycle. The maximum leverage occurs during the preliminary design stage and declines to almost nil in advanced stages of production.

Historically, designing to lower cost has taken a back seat to other requirements in the design of airframe structures. Structural integrity, durability, etc, always took precedance over cost. Too often cost trades were only conducted when the drawing release schedules permitted.

Cost trades are frequently accomplished by design producibility and cost estimating staffs. Because of the large ratio of designers to cost analysts, the number of trades which can be exercised during the initial design phase prior to drawing release exceeds the capacity of the cost analysis staff. In the future the designer, equipped with computerized cost information presented in acceptable formats, will conduct trade-off studies himself and will further be stimulated to develop innovative structural design concepts to reduce cost.

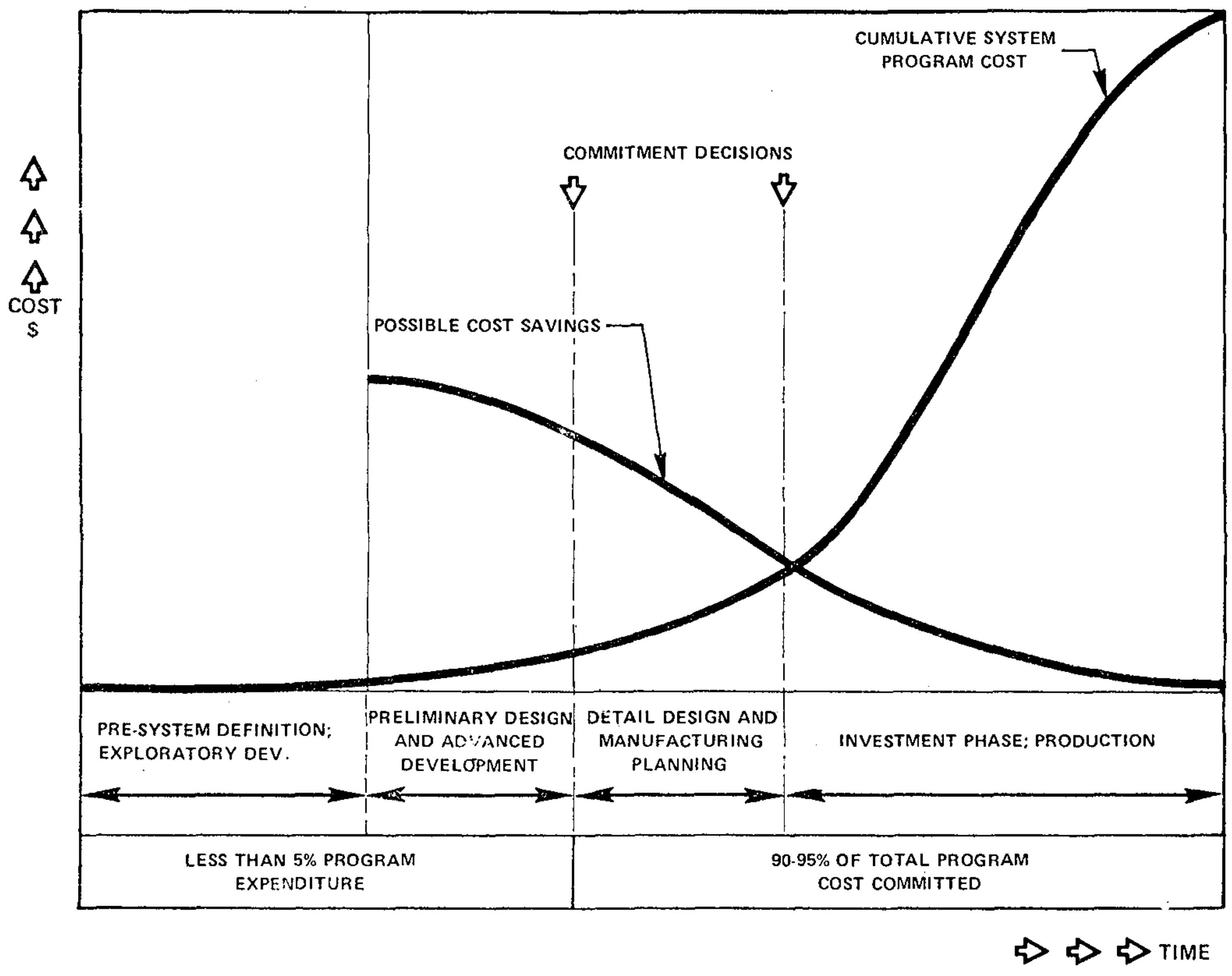


FIGURE B-4. COST REDUCTION LEVERAGE FOR AIRFRAME DESIGNERS

Problems When Replacing Metals with Composites

The importance of the problem of designing to lower cost cannot be over stressed and the following example serves to illustrate the problem which can occur when replacing a conventional design with a new material even when weight and cost advantages are achieved.

Performance/cost-trade studies to reduce both weight and cost of airframes were conducted in the program on "Manufacturing Methods for Metal-Matrix Structural Components", conducted by General Dynamics, Convair Division, and Rockwell International(7). The AFML program set out to unify the results of recent advances with the boron/aluminum, metal-matrix, composite material used for the NASA Space-Shuttle fuselage truss system, and manufacturing methods. It also set out to demonstrate the near term cost and weight savings of boron/aluminum for major aircraft programs such as the U.S.A.F. B-1.

Five components from the B-1 were examined to assess the potential application of boron/aluminum as a replacement for the baseline structure. The following components were studied by the General Dynamics/Rockwell International team:

- Aft fuselage stub frame
- Nacelle support beam in aft intermediate fuselage
- Stringer in wing carry-through structure
- Outboard closure rib of wing carry-through structure
- Wing root structure rib.

When this study was initiated the baseline configuration was, with the exception of the nacelle beam, machined and diffusion-bonded titanium. The nacelle beam was a machined titanium forging.

The results of this study, which included the fabrication and test of the wing rib panel, are summarized in Tables B-3 and B-4, showing the weight and cost values, respectively(7)

TABLE B-3. AVERAGE WEIGHTS OF TITANIUM BASELINE AND METAL-MATRIX COMPOSITE STRUCTURE FOR PRODUCTION QUANTITY OF 250 (7)

COMPONENT	WEIGHT (LB)		
	ALL-TITANIUM	B/Al-TITANIUM-Al	SAVINGS (%)
STUB FRAME	96	73	24
NACELLE BEAM	155	142	8
STRINGER	76	34	56
WING CARRY-THROUGH RIB	351	253	28
WING RIB PANEL	150	99	34

TABLE B-4. AVERAGE COSTS OF TITANIUM BASELINE AND METAL-MATRIX COMPOSITE STRUCTURE FOR PRODUCTION QUANTITY OF 250(7)

COMPONENT	COST ($1,000)		
	ALL-TITANIUM	B/Al-TITANIUM-Al	SAVINGS (%)
STUB FRAME	13.6	7.9	42
NACELLE BEAM	14.9	17.9	*(20.1)
STRINGER	11.9	3.7	69
WING CARRY-THROUGH RIB	32.8	25.0	24
WING RIB PANEL	12.1	7.1	40

*( ) COST PENALTY

During the evolution of all engineering systems in the increasingly cost-conscience environment, iterations are constantly under way with the materials and processes being used in production. Improvements can occur with the baseline structure with which all alternative approaches are compared and, also, the aircraft operating environment becomes more accurately defined, frequently alleviating the thermal and other conditions. The latter is believed to have been the case in the development wing-rib panel for the B-1. In spite of the favorable weight and cost payoffs shown in Tables B-3 and B-4, the comparison was made with the baseline structure and design objectives at the point of initiation of the composites program and it was not possible to substitute later the metal-matrix composite and process technologies for the production component.

The question of more accurately defining the vehicle operating environment seems to be unavoidable. However, progress with conventional and advanced metallic materials and processes must also be appreciated and considered when planning and carrying out programs involving advanced composite materials. It is therefore now considered appropriate to address this emerging problem of future competition between the metal and composite technologies.

While promising advanced composite materials are being evaluated in NASA and Defense flight-service programs, advanced metallic structural development programs are also underway. New configurations and manufacturing processes are expected to improve the efficiency of structures utilizing conventional materials. These structures will also be categorized as "advanced". The increased usage of adhesives, weld-bonding and rivet-bonding, will, for example, enhance the opportunities for designers to develop fresh approaches to reduce acquisition and life-cycle costs. It is appropriate to summarize the objectives of current advanced metallic programs. The goals of this parallel effort to composites, are as follows:

- Acquisition Cost Reduction - Achieve a <u>20-30 percent reduction</u> in the cost of metallic airframes

- Cost of Ownership Reduction - Achieve a *15-20 percent reduction* in funds expended in maintenance of metallic airframes
- Improved Structural Integrity - Provide the approaches whereby new requirements in the areas of safety, durability, and life management can be implemented with *no* increase in cost
- Extended Performance - Assure availability of the metals technology required for future high performance aircraft.

The following is a brief summary indicating the efforts underway to achieve the above objectives:

- Simplified design configurations
- Manufacturing innovation, e.g., computer-aided forming methods
- Elimination or reduction of fasteners
- Reduce part-count through unitized structures, castings, etc.
- Reduction of machining improving material utilization factors
- Reduction of tooling and assembly costs, e.g., through weld-bonding
- Increased use of adhesive-bonding for primary structures.

Opportunities to Reduce Cost with Manufacturing Technology

Due to the severe design-to-cost environment imposed on the production of composite structures, it is essential that the major cost drivers be identified early in the programs and their reduction addressed from the outset. As examples of this type of information, the cost drivers for fiberglass honeycomb laminates and adhesive bonding are shown in Figures B-5 and B-6(5). It should be noted that these figures are not quantitative as they only indicate the formats acceptable to designers.

The design of tools which circumvent the autoclave for curing and bonding composite structures is an area which requires further development. For some complex structural configurations, the autoclave is becoming a major cost-driver because of energy requirements and, for example, new types of tools are being developed to fabricate helicopter rotor-blades. An example of such tools is as follows:

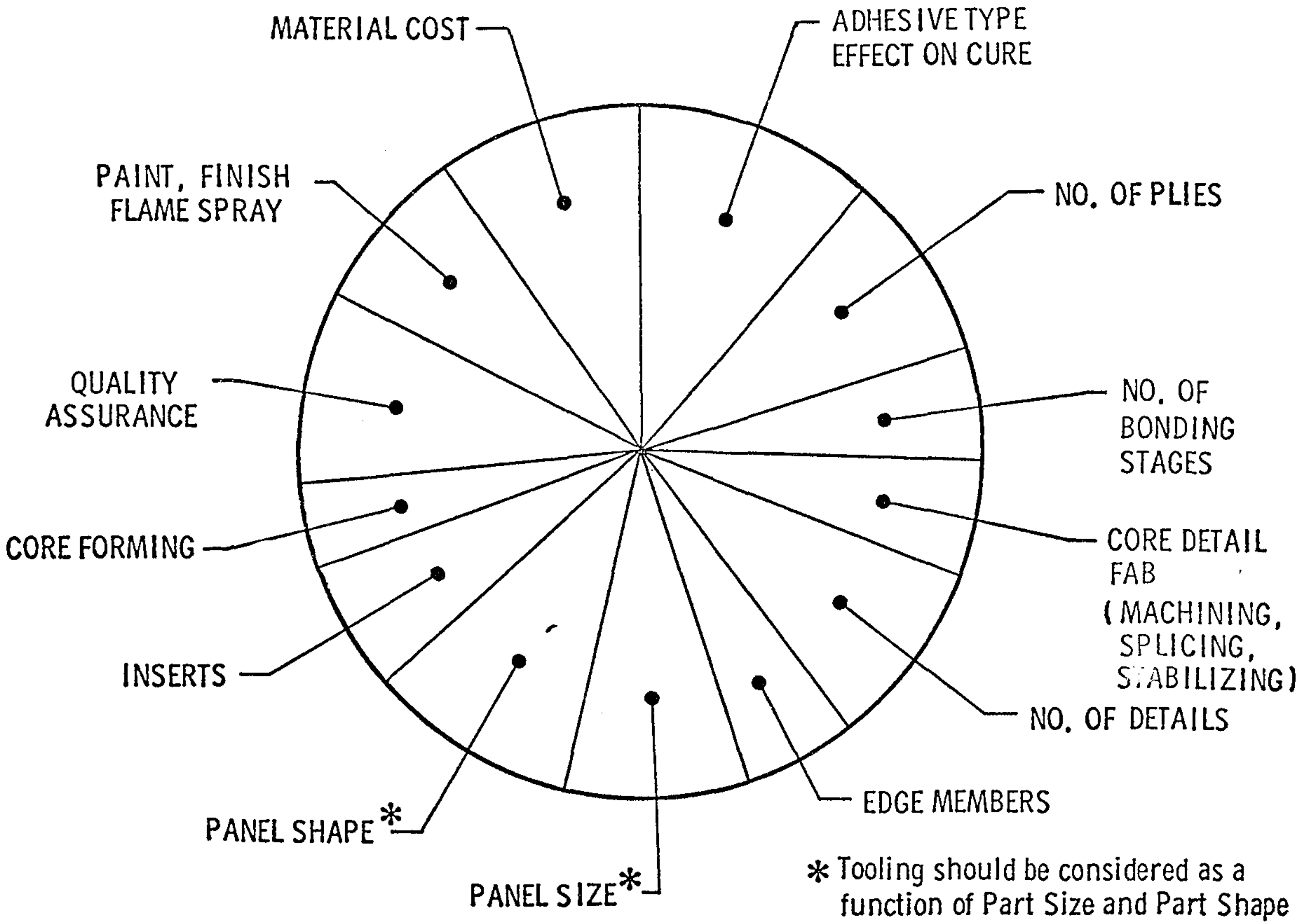
- Integrally-heated, cooled and pressurized tools designed for both prototype and production structures providing
  - reduced lead-time
  - cost reduction through labor savings
  - energy conservative concept
  - reduced possibility for extensive hardware losses (as can occur in an autoclave)
  - increased rate of production due to more rapid heating and cooling.

However, integrally-heated tooling requires a strong interface between materials, process, tooling, and design. Extensive thermal analysis is required to optimize the heat transfer efficiency of such tools and innovative heating/cooling concepts need to be developed.

It is desirable to continue development of pultrusion machines to produce "basic" shapes, e.g., sandwich closeout-members and Z-stringers, designed for greater part standardization throughout fuselage and other subassemblies. Hand-fitting and subsequent high NDT costs will, in this way, be drastically reduced.

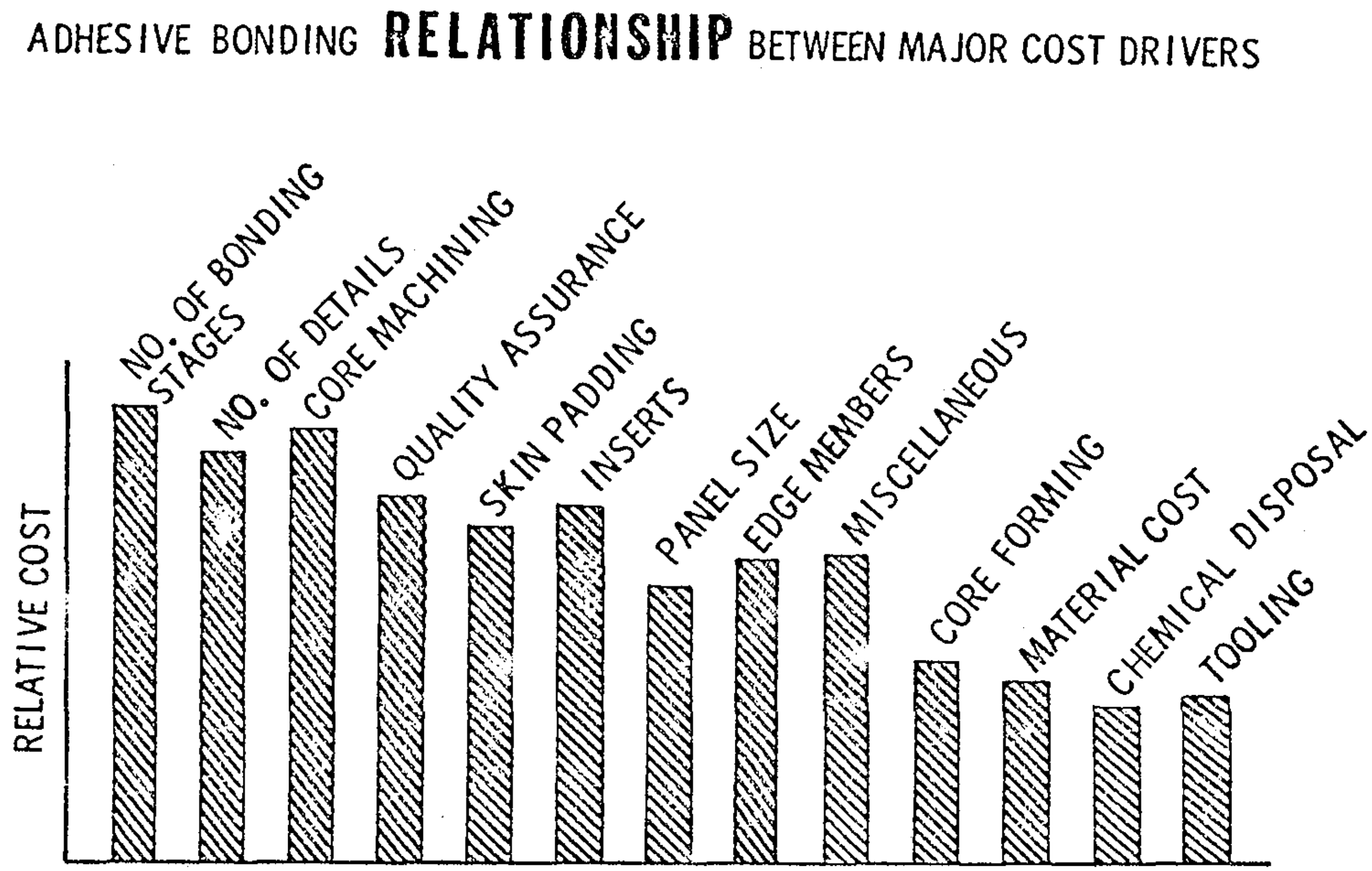
Another manufacturing method is to produce flat sheets with complex fiber orientations using computer-aided filament-winding techniques and produced on a large mandrel. The composite cylinder is then cut longitudinally and laid flat. This method is in use at Messerschmitt-Bölköw-Blohm, GmbH., Ottobrunn, Germany, for rotor-blade skins.

FIBERGLASS HONEYCOMB LAMINATES RELATIONSHIP BETWEEN MAJOR COST DRIVERS



* Tooling should be considered as a function of Part Size and Part Shape

FIGURE B-5. FIBERGLASS HONEYCOMB PANEL COST-DRIVERS (5)



RELATIONSHIP BASED ON:

	EXAMPLE
PART CONFIGURATION	TRAILING EDGE CONTROL SURFACE
MATERIAL	AL. SKIN - AL H/C
SIZE	LARGE TRANSPORT
QUANTITY	200 AIRPLANE PROGRAM

FIGURE B-6. ADHESIVE BONDING COST-DRIVERS(5)

A further cost saving opportunity for sandwich structures is to develop equipment to reduce the cost of machining complex configurations in Nomex honeycomb cores. Lower cost glass-fiber reinforced plastic honeycomb cores also need to be developed. Few developments have occurred with honeycomb cores during the past 25 years. Cores need to be developed which avoid or very much reduce the expensive and time-consuming machining operations, but which at the same time do not compromise strength, stiffness, and other properties.

Hand-finishing operations for composite structures need to be reduced as they represent a significant part of the total component cost. It has been found that composite structures in service on helicopters sometimes require paint stripping which is also an expensive operation. There is a need for programs centered on simplifying these procedures.

There is a need to develop design-oriented tape-laying machines possibly with, for example, heating shoes to circumvent or reduce the autoclave curing cycle by simultaneously providing curing of the tape. However, it is also necessary to produce "dedicated" machines which may be more limited in scope than the complex multifunctional equipment currently available. Such equipment may not attempt to layup the entire structure. Smaller machines should be designed to reduce or avoid hand-layup in local areas which, for example, is frequently necessary at wing-spar cap and root connections. This is an example of the requirement of a strong design/manufacturing methods interface which avoids prejudices and conservative practices that occur in these disciplines. This presents an opportunity to extend the boundaries of the disciplines(8)

Potentially promising opportunities to reduce cost of composite structures are by methods such as braiding developed by McDonnell-Douglas Corporation, St. Louis, Missouri, to produce enclosed structures. Weaving has been also applied for flat structures(9) Further, structural channel members have been braided in which rings and attachment fittings have been integrally braided into the composite structure reducing part-count, joining complexity and therefore cost. Computer-aided design and manufacturing methods (CADAM) can be applied to these processes and, furthermore, hybridized structures employing combinations of fibers, for example, S-glass, Thornel T-300, and Kevlar-49 can be produced.

Conclusions and Recommendations

General

(1) The United States appears to be at least 4 years ahead of European countries with advanced composite applications to military fixed and variable sweep aircraft and to civil aircraft structural developments. Maintaining this lead will provide U. S. companies with a commanding position and valuable leverage in negotiating agreements, air transport sales, and subassembly production. The composite capabilities and facilities acquired in the United States will result in decisions being made to produce such structures here in future consortium agreements.

(2) The cost of flight-test and data reduction of civil aircraft is high ($30,000/hour) and might reduce the availability of funds for technological developments. Warranties represent a further financial problem.

(3) Since 1943, problems of lack of automated fabrication methods, limited service data and questionable cost estimates have hindered the use of glass-reinforced plastics in aircraft primary structures, with the exception of the specialized rotor-blade.

(4) The experience with the advanced composite horizontal stabilizers on the F-14, F-15, and F-16 aircraft will prove to be important for the commercial airplane companies. The transfer of this experience from military to civil structures using analytical modeling is important. Spin-off from military STOL structures technology to civil transport design is expected.

Education and Retraining

(5) The problem of the aging design staffs will require the training of new generations of designers. The current NASA-sponsored program at Rensselaer Polytechnic Institute is a timely and important step.

(6) Aerospace companies will need to retrain engineers and designers in composite technologies well in advance of eventual production commitments being made. Large numbers of engineers are required throughout the program.

On Design

(7) Strong materials/fabrication/design/NDE interfaces must be developed in all programs. Excellent progress has been made, but the interfaces need to be further strengthened.

(8) Design for ease of nondestructive evaluation, maintenance and repair are high priority considerations to reduce life-cycle costs.

(9) For some composite components, it may be necessary to provide an alternative structure. When this can be done, the composite component will be looked upon more favorably should a technical or economic problem occur.

Metallic Versus Composite Structures

(10) The design objectives of advanced metallic programs, concurrently underway with composite programs, suggest developmental trends with these competing materials. If successful, the designers will have a broad choice of structural possibilities. The composite teams should be aware of these objectives, examples of which are:

- 20-30 percent reduction in acquisition cost
- 15-20 percent reduction in maintenance cost
- Improved structural integrity at no increase in cost
- Extended performance through availability of new metals technology.

(11) During the development of major composite structures being compared with a baseline metallic counterpart, it is imperative that the evolution of improved definitions of design objectives be tracked. Design goals change, e.g., thermal environments, yet comparisons are most frequently made with those goals defined at the outset of the program being run to demonstrate a new technology.

(12) During the development of demonstration composite structures being evaluated with a metallic counterpart as the baseline, it is imperative that developments that continuously occur with metallic structures, be closely followed. It is advisable to determine, firstly, whether or not significant improvements can still be made with the baseline structure through the use of alternative processing technologies or modifications of the design configuration. As competitive technologies appear, more attention will be devoted to upgrading conventional technologies and improvements can be expected.

Selective Reinforcement

(13) The application to civil transports of glass-reinforced plastic laminates "spiked" or selectively reinforced with graphite fibers is important. This use will enable airlines to acquire experience, as soon as possible, with this "new" fiber.

Secondary Structures

(14) Secondary structures provide unique opportunities to reduce weight and cost, using, for example, molded graphite- einforced thermoplastic sheets, chopped fibers, braiding, and weaving. Families of components with a commonality of geometry can be developed. Use of composites of these types and forms should be further stimulated and high-volume commercial fabrication methods closely followed. Metal secondary components can be more expensive items than primary parts. Composites will alleviate corrosion problems which airlines sometimes experience with secondary structures, particularly due to some types of cargo.

Design to Lower Cost

(15) Composites should enable lead-times to be reduced compared with that required, for example, for forging dies. Designers should therefore find more time available to conduct manufacturing cost/design trades.

(16) Programs need to be directed to providing all the information required by the preliminary designer to facilitate his decisions and to stimulate innovative

approaches. It is at this stage in the design process that the leverage and "window of opportunity" exists in reducing cost, improving damage-tolerance, and achieving other objectives.

(17) Efforts should be made to provide the designers with relative and quantitative information on cost-drivers at all stages of composite material development so that reduction can be addressed.

(18) Cost information on all aspects of composite development and use must be developed from the outset of programs involving this material and presented in a format usable by preliminary and detail designers. Such information on metals enabling manufacturing cost/design trade-offs to be conducted is being developed for the designers. Composites will be competing with metals in the design-to-lowest cost environment which will become increasingly severe.

(19) When composites are applied on a substitution basis for a product already in production, the learning curves of composite and metallic structures may never intersect as the metallic parts will be at an advanced point on the learning curve. A more favorable position is achieved when the designer has the confidence to apply new materials at the preliminary design stage.

Cost Reduction Opportunities

(20) The development of new designs of tools and processes is required to improve energy utilization during the manufacturing operations. Energy utilized by autoclaves is a cost-driver for structures of complex geometries where numbers of components cannot be curved simultaneously. Examples of tooling developments are:

- Integrally heated manifold tools
- Pultrusion equipment
- "Dedicated" design-oriented, limited scope, tape-laying equipment
- Computer-aided winding equipment to produce flat sheets
- Braiding and weaving processes.

(21) To reduce cost, the development of alternative designs of honeycomb cores and machining equipment for cores are attractive opportunities.

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